Quark-quark scattering contributions to high-energy total cross sections

D. Mark Manley
Department of Physics and Center for Nuclear Research, Kent State University, Kent, Ohio 44242
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It is shown that total hadronic cross sections are described well by considering single- and double-scattering contributions from quark-quark scattering. With an energy-dependent form suggested by Regge theory, all high-energy total cross sections can be fitted successfully and efficiently using a small number of free parameters. [S0556-2821(97)03123-8]

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I. INTRODUCTION

Since hadrons are bound states of three quarks (or antiquarks), or of a quark and an antiquark, we expect that it should be possible to describe high-energy hadron-hadron cross sections in terms of contributions from quark-quark scattering. In the additive quark model, only single-scattering contributions to the forward amplitude are included. The optical theorem can then be used to relate the forward scattering amplitude to the total cross section. We denote the single-scattering contributions to the total hadronic cross sections as $S_u=\sigma(uu)$, $S_{\bar{u}}=\sigma(u\bar{u})$, and $S_s=\sigma(us)$, where, following Lipkin [1], we assume that $\sigma(uu)=\sigma(dd)=\sigma(ud)=\sigma(u\bar{d})=\sigma(d\bar{u})$, $\sigma(u\bar{u})=\sigma(d\bar{d})$, and $\sigma(us)=\sigma(ds)=\sigma(u\bar{s})=\sigma(d\bar{s})=\sigma(\bar{s}u)=\sigma(\bar{s}d)$. The Glauber approximation [2] may be used to find multiple-scattering corrections [3,4]. Here we limit our discussion to double-scattering corrections, and we denote these contributions to the total hadronic cross sections as δ_{uu}, $\delta_{u\bar{u}}$, $\delta_{\bar{u}\bar{u}}$, $\delta_{u\bar{s}}$, δ_{us}, and δ_{ss}. With our notation, $\delta_{q_1q_2}$ describes a contribution from a uq_1 and uq_2 double scattering. (Isospin symmetry is assumed throughout.) For example, δ_{us} describes a contribution from a uu and us double scattering. We may then write the hadronic total cross sections as follows:

$$\sigma(\pi^-p)=4S_u+2S_{\bar{u}}+6\,\delta_{uu}+\delta_{\bar{u}\bar{u}}+8\,\delta_{u\bar{u}}, \tag{1a}$$

$$\sigma(\pi^+p)=5S_u+S_{\bar{u}}+10\delta_{uu}+5\,\delta_{u\bar{u}}, \tag{1b}$$

$$\sigma(K^-p)=S_u+2S_{\bar{u}}+3S_s+\delta_{\bar{u}\bar{u}}+2\,\delta_{u\bar{u}}+6\,\delta_{u\bar{s}}+3\,\delta_{us}+3\,\delta_{ss}, \tag{1c}$$

$$\sigma(K^+p)=\sigma(K^+n)=3S_u+3S_s+3\,\delta_{uu}+9\,\delta_{us}+3\,\delta_{ss}, \tag{1d}$$

$$\sigma(K^-n)=2S_u+S_{\bar{u}}+3S_s+\delta_{uu}+2\,\delta_{u\bar{u}}+3\,\delta_{u\bar{s}}+6\,\delta_{us}+3\,\delta_{ss}, \tag{1e}$$

$$\sigma(\bar{p}p)=4S_u+5S_{\bar{u}}+6\,\delta_{uu}+10\delta_{\bar{u}\bar{u}}+20\delta_{u\bar{u}}, \tag{1f}$$

$$\sigma(\bar{p}n)=5S_u+4S_{\bar{u}}+10\delta_{uu}+6\,\delta_{\bar{u}\bar{u}}+20\delta_{u\bar{u}}, \tag{1g}$$

$$\sigma(pp)=\sigma(pn)=9S_u+36\delta_{uu}, \tag{1h}$$

$$\sigma(\Sigma^-p)=\sigma(\Sigma^-n)=6S_u+3S_s+15\delta_{uu}+18\delta_{us}+3\,\delta_{ss}, \tag{1i}$$

$$\sigma(\Xi^-p)=\sigma(\Xi^-n)=3S_u+6S_s+3\,\delta_{uu}+18\delta_{us}+15\delta_{ss}, \tag{1j}$$

$$\sigma(\Omega^-p)=\sigma(\Omega^-n)=9S_s+36\delta_{ss}. \tag{1k}$$

We have included expressions for the ΩN total cross section, although no high-energy data are currently available. Note also that the ΛN and ΣN cross sections are expected to be equal at high energies. Experimentally, observed hadronic cross sections are consistent with the ratios $\sigma(\pi^-p)-\sigma(\pi^+p)$: $\sigma(K^-n)-\sigma(K^+n)$: $\sigma(K^-p)-\sigma(K^+p)$: $\sigma(\bar{p}n)-\sigma(pn)$: $\sigma(\bar{p}p)-\sigma(pp)$ = 1 : 1 : 2 : 4 : 5. These ratios imply that $\delta_{uu}=\delta_{\bar{u}\bar{u}}=\delta_{\bar{u}\,\bar{u}}$ and $\delta_{us}=\delta_{u\bar{s}}$. In the following discussion, we assume that these relations are valid, at least approximately, so that all hadronic cross sections may be expressed in terms of just six quantities: S_u, $S_{\bar{u}}$, S_s, δ_{uu}, δ_{us}, and δ_{ss}.

II. PARAMETRIZATION

We found it convenient to parametrize the single-scattering contributions to the hadronic cross sections (in mb) using the Donnachie-Landshoff form [5], which was inspired by Regge theory:

$$\sigma(uu)=S_u=X_us^{\epsilon}+Y_us^{-\eta}, \tag{2a}$$

$$\sigma(\overline{uu})=S_{\bar{u}}=X_us^{\epsilon}+Y_{\bar{u}}s^{-\eta}, \tag{2b}$$

$$\sigma(us)=S_s=X_ss^{\epsilon}. \tag{2c}$$

Donnachie and Landshoff fitted total cross sections for nine reactions, including pp, pn, $\bar{p}p$, $\bar{p}n$, π^-p, π^+p, K^-p, K^+p, and γp. A total of 13 free parameters was needed to fit the eight hadronic reactions. The energy-dependent form was a sum of two powers:

$$\sigma_{\rm tot}=Xs^{\epsilon}+Ys^{-\eta}, \tag{3}$$

where the first term arises from Pomeron exchange and the second from ρ, ω, f, and a exchange. In Eq. (2c) above, there is no coefficient Y_s in S_s because of Zweig's rule: the only nonstrange Regge exchange coupling the u and d quarks to the s quark is the Pomeron. It has been long known

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that the ρ, ω, f, and a trajectories must be, at least approximately, degenerate. Let us consider masses for established mesons (ρ and a, with $I=1$, and ω and f, with $I=0$) from the most recent *Particle Data Group book* [6]. Using $M=0.769$ GeV for the $\rho(770)$ and $M=0.782$ GeV for the $\omega(782)$ with $J^P=1^-$, $M=1.318$ GeV for the $a_2(1320)$ and $M=1.275$ GeV for the $f_2(1270)$ with $J^P=2^+$, $M=1.691$ GeV for the $\rho_3(1690)$ and $M=1.667$ GeV for the $\omega_3(1670)$ with $J^P=3^-$, and $M=2.044$ GeV for the $f_4(2050)$ with $J^P=4^+$, the data are fitted well with the linear trajectory, $\alpha(t)=0.53+0.85t$, where $J=\alpha$ and $t=M^2$ in GeV^2. Since a Regge trajectory asymptotically contributes a power $s^{\alpha(0)-1}$ to $\sigma_{\rm tot}$, we expect that $\eta \sim 0.47$.

Donnachie and Landshoff first made a simultaneous five-parameter fit to the pp and $\bar{p}p$ data for $\sqrt{s}>10$ GeV, from which they determined $\epsilon=0.0808$ and $\eta=0.4525$. They then used these parameters for all subsequent fits. For each other pair of hadronic reactions, ab and $\bar{a}b$, they had three new free parameters: a common X, and a Y for each. Since there are fewer data for the other reactions, they went down to $\sqrt{s}=6$ GeV for those fits. A suitable fit for pp and pn data was obtained using a common X for both reactions.

Total cross sections for 14 hadronic reactions were fitted simultaneously in the present work. In addition to the eight hadronic reactions investigated by Donnachie and Landshoff, data were fitted for the reactions K^-n, K^+n, Σ^-p, Σ^-n, Ξ^-p, and Ξ^-n. (Total cross sections for π^-n and π^+n were also fitted to increase the data base; however, by charge symmetry, the cross sections for these reactions are equal to those for π^+p and π^-p, respectively.) The data come from a 1988 compilation [7], supplemented by the final E-710 [8] and Collider Detector at Fermilab (CDF) [9] values of $\sigma(\bar{p}p)$ at $\sqrt{s}=1800$ GeV, and at 546 and 1800 GeV, respectively. The CDF value of 80.03 ± 2.24 mb at 1800 GeV is significantly larger than the final E-710 value of 72.8 ± 3.1 mb, measured at the same energy. (The CDF measurements were not available for the Donnachie-Landshoff fit.)

III. RESULTS AND DISCUSSION

We performed two global fits. In our first fit, we parametrized the double-scattering terms to have the same form as the single-scattering terms:

$$\delta_{uu}=X_{uu}s^{\epsilon}+Y_{uu}s^{-\eta}, \tag{4a}$$

$$\delta_{us}=X_{us}s^{\epsilon}+Y_{us}s^{-\eta}, \tag{4b}$$

$$\delta_{ss}=X_{ss}s^{\epsilon}. \tag{4c}$$

The purpose of this fit was to see whether or not it was possible to reproduce the results of the Donnachie-Landshoff (DL) fits within the general quark-model constraints imposed by Eqs. (1). For this purpose, we set $\epsilon=0.0808$ and $\eta=0.4525$, the values obtained by Donnachie and Landshoff. The recent CDF [9] measurements of $\sigma(\bar{p}p)$ at $\sqrt{s}=546$ and 1800 GeV were not included for this fit. Table I gives values of the parameters obtained for fit 1, and Table II compares the corresponding X and Y coefficients of the hadronic cross sections with the results of the DL fit. As can be seen, we are able to reproduce the DL values quite well while at the same time fitting data adequately for several additional reactions. The fitted total hadronic cross sections obtained by fit 1 are virtually indistinguishable from those shown in DL's Fig. 1 [5]. There are, however, at least two possible shortcomings of this fit. First, this fit predicts that at high energies, $\sigma(Kp)=0.87\sigma(\pi p)$, which implies some mysterious flavor-dependent effect. That is, we expect the pomeron to have the same coupling to the strange quark as to the lighter quarks. In addition, this fit significantly disagrees with results of the new CDF measurement of $\sigma(\bar{p}p)$ at $\sqrt{s}=1800$ GeV, which was unavailable at the time of the DL

TABLE I. Values of the fitted parameters for fit 1 (with nine free parameters for the hadronic reactions) and fit 2 (with ten free parameters for the hadronic reactions, using the constraint $X_s=X_u$), as described in the text. The coefficients X, Y, and Z have units of millibarns. Uncertainties in the last significant figure are given in parentheses. No uncertainties are given for parameters held fixed in a fit.

Parameter	Fit 1	Fit 2
ϵ	0.0808	0.1340(57)
η	0.4525	0.492(12)
ζ		0.139(22)
X_u	2.012(11)	1.374(51)
Y_u	−1.52(13)	1.42(26)
$Y_{\bar{u}}$	7.21(13)	11.64(51)
X_s	1.619(30)	
X_{uu}	0.1025(31)	−0.00977(91)
Y_{uu}	1.856(37)	0.09(25)
Z_{uu}		0.78(17)
X_{us}	0.0546(86)	
Y_{us}	0.859(50)	1.031(53)
X_{ss}	0.058(13)	
$\gamma_{\rm scale}$	0.004824(10)	0.004830(10)

TABLE II. Coefficients (in mb) from the Regge-type fits of total cross sections. The exponents for fit 1 of the present work were $\epsilon=0.0808$ and $\eta=0.4525$, as determined in Ref. [5] by Donnachie and Landshoff (see text).

	DL (Ref. [5])		This work (fit 1)	
Reaction	X	Y	X	Y
π^-p	13.63	36.02	13.61	36.20
π^+p	13.63	27.56	13.61	27.47
K^-p	11.82	26.36	11.87	26.21
K^+p	11.82	8.15	11.87	8.75
K^-n			11.87	17.48
K^+n			11.87	8.75
$\bar{p}p$	21.70	98.39	21.80	96.81
pp	21.70	56.08	21.80	53.16
$\bar{p}n$	21.70	92.71	21.80	88.08
pn	21.70	54.77	21.80	53.16
ΣN			19.63	34.21
ΞN			17.92	16.49
ΩN			16.67	0.00
γp	0.0677	0.129	0.0657	0.154

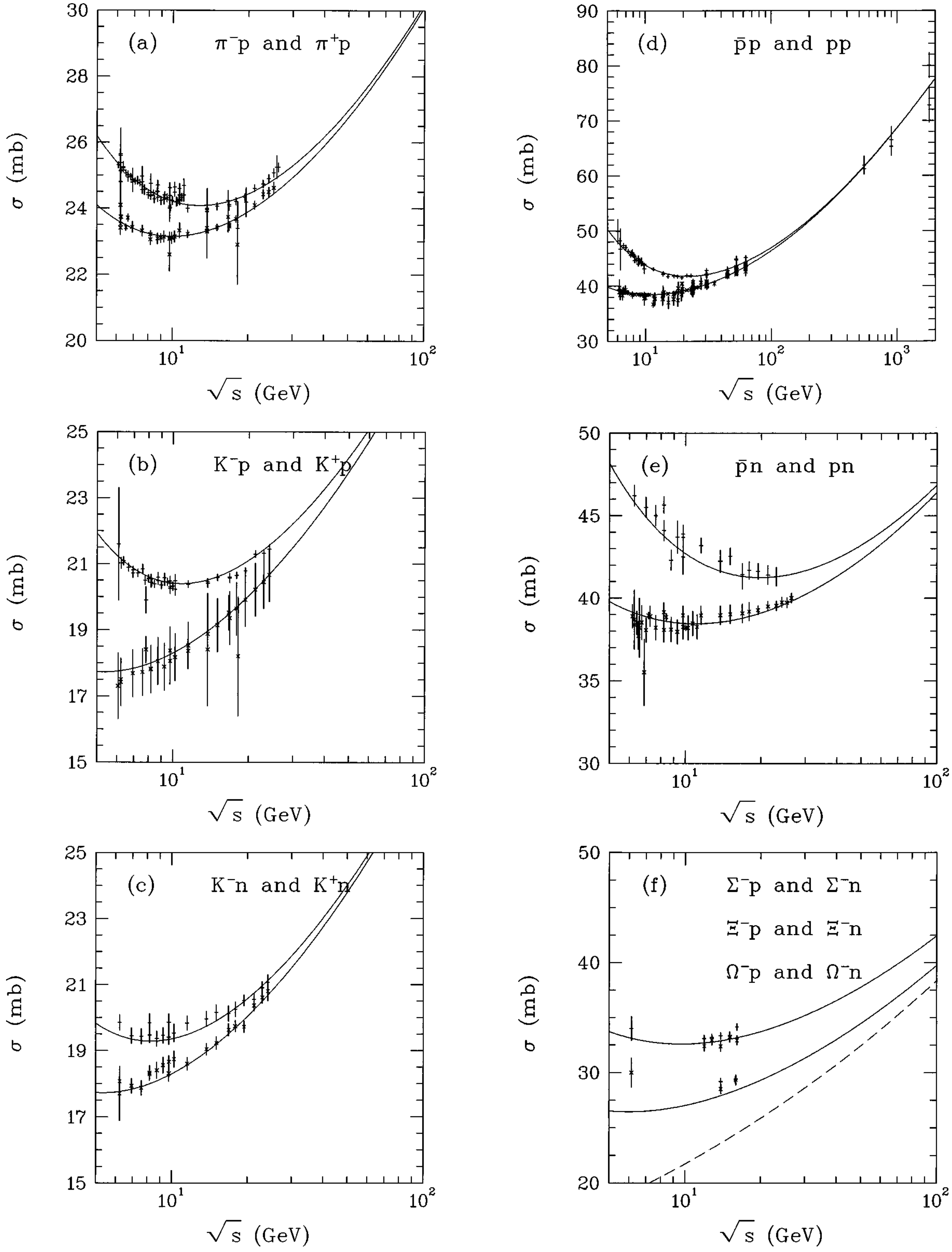

FIG. 1. (a) Total cross-section data for $\pi^- p$ (+) and for $\pi^+ p$ (×); (b) data for $K^- p$ (+) and for $K^+ p$ (×); (c) data for $K^- n$ (+) and for $K^+ n$ (×); (d) data for $\overline{p}p$ (+) and for pp (×); (e) data for $\overline{p}n$ (+) and for pn (×); and (f) [top] data for $\Sigma^- p$ (+) and for $\Sigma^- n$ (×), and [bottom] data for $\Xi^- p$ (+) and for $\Xi^- n$ (×): the lowest (dashed) curve shows the predicted total cross section for $\Omega^- p$ and for $\Omega^- n$. All curves shown represent the results of the second global fit discussed in the text.

analysis. Of course, one also does not expect the double-scattering terms to have the same energy dependence as the single-scattering terms. Because of these concerns about this fit, we performed a second fit, which fits the data better and which we feel is more physically realistic.

In the second fit, we assumed a more suitable energy dependence for the double-scattering terms:

$$\delta_{uu} = X_{uu} s^{2\epsilon} + Y_{uu} s^{\epsilon-\eta} + Z_{uu} s^{-\zeta}, \qquad (5a)$$

$$\delta_{us}=X_{uu}s^{2\epsilon}+Y_{us}s^{\epsilon-\eta}, \quad (5b)$$

$$\delta_{ss}=X_{uu}s^{2\epsilon}. \quad (5c)$$

This fit had a total of ten free parameters: ϵ, η, ζ, X_u, Y_u, $Y_{\bar{u}}$, X_{uu}, Y_{uu}, Z_{uu}, and Y_{us}. For this fit, flavor independence was assumed for the pomeron terms by setting $X_s=X_u$ in the single-scattering terms and by using a common coefficient X_{uu} in the double-scattering terms. Thus, the meson-baryon and baryon-baryon cross sections, respectively, become equal at sufficiently high energies, as one might expect. We assumed that the leading-order term for the double-scattering terms at high energy is proportional to $s^{2\epsilon}$, as expected, for example, from using the Glauber approximation. We also included the next-to-leading-order term for δ_{uu} and δ_{us}, which should be proportional to $s^{\epsilon-\eta}$. There also should be a term in δ_{uu} proportional to $s^{-2\eta}$, which should be small at these energies and has been neglected. Instead we included a term proportional to $s^{-\zeta}$, where the fitted value of the exponent was $\zeta=0.139\pm0.022$. The physical origin of this term is unclear, although it presumably arises from either the real part of the quark-quark scattering amplitude or from a nonforward contribution to the quark-quark scattering amplitude.

The total χ^2 for our preferred fit, fit 2, was significantly lower than for fit 1, which did not include the recent CDF measurements [9] of $\sigma(\bar{p}p)$ at $\sqrt{s}=546$ and 1800 GeV. Table I includes values of the parameters obtained for fit 2. The fitted value of $\eta=0.492\pm0.012$ is in good agreement with the value of about 0.47 expected from Regge theory. Our fitted value of $\epsilon=0.1340\pm0.0057$ is also closer to the range, 0.15–0.17, calculated within the framework of QCD [10], than the value 0.0808 of Donnachie and Landshoff [5]. Over the entire energy range fitted, we found little difference in the quark-quark cross sections S_u and S_s, which indicates that the imaginary parts of the forward quark-quark scattering amplitudes F_{uu} and F_{us} are approximately equal. (It does not necessarily follow, however, that there are negligible differences in the nonforward amplitudes.)

In high-energy hadron-deuteron scattering [11], for example, double-scattering corrections to the cross sections are found to be negative because the hadron-nucleon forward scattering amplitudes are predominantly imaginary at high energies. (A predominantly imaginary amplitude results from the increasing importance of inelastic scattering at high energies.) The results of our second fit are, in fact, consistent with the quark-quark double-scattering terms becoming negative at high energies. In particular, we find that δ_{ss} is small and negative over the entire energy range fitted; however, δ_{us} does not become negative until $\sqrt{s}\approx40$ GeV, and δ_{uu} remains positive until about 200 GeV. Thus, at energies where most of the present data exist (below about 30 GeV), we expect the real parts of the forward quark-quark amplitudes to be relatively large. This result is in qualitative agreement with the recent determination by Donnachie and Landshoff of a large real part for the $\rho°p$ amplitude at high energies [12].

Results of the second global fit are shown in Fig. 1. In general, the predicted cross sections for $\sqrt{s}>100$ GeV are higher than those of the DL fit. As shown in Fig. 1(d), our

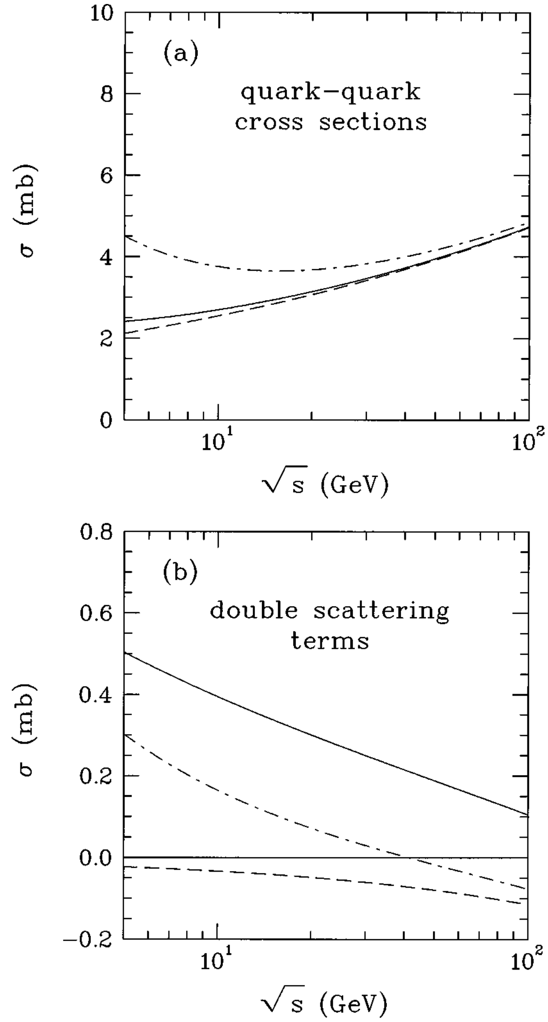

FIG. 2. (a) Total quark-quark cross sections. The upper dashed-dotted curve shows $\sigma(\bar{u}u)$, the middle solid curve shows $\sigma(uu)$, and the slightly lower dashed curve shows $\sigma(us)$; (b) double-scattering contributions to the hadronic total cross sections. The upper solid curve shows δ_{uu}, the middle dashed-dotted curve shows δ_{us}, and the lower dashed curve shows δ_{ss}.

fitted $\sigma(\bar{p}p)$ cross section of 76.2 mb at 1800 GeV is intermediate between the measured CDF and E-710 values at the same energy. Figure 1(f) displays results of the fit for the ΣN, ΞN, and ΩN total cross sections. Most of the ΣN and ΞN cross sections are from a single experiment using the hyperon beam at the CERN Super Proton Synchrotron (SPS) [13]; the ΩN cross section is a prediction of the fit. For fit 2 in the asymptotic limit, the total cross sections for NN, $\bar{N}N$, ΣN, ΞN, and ΩN become equal; similarly, the total cross sections for πN and KN become equal in the asymptotic limit. Except for a single early measurement of $\sigma(\Sigma^-n)$ at $\sqrt{s}=6.1$ GeV [14], the available data agree with the predictions that $\sigma(\Sigma^-p)=\sigma(\Sigma^-n)$ and that $\sigma(\Xi^-p)=\sigma(\Xi^-n)$.

The extracted quark-quark total cross sections are shown in Fig. 2(a) for fit 2. Similarly, Fig. 2(b) shows the double-scattering contributions. Note that by $\sqrt{s}=100$ GeV, the quark-quark cross sections are all equal to about 4.7 mb. It is interesting to calculate the contributions to the total cross sections from quark double-scattering effects at different energies. For example, the fitted pp total cross section (for fit 2) at $\sqrt{s}=100$ GeV is 46.5 mb, with a contribution of 3.8 mb, or 8.1%, from double scattering. Of this, there is a (negative) contribution of 4.2 mb, or 8.9%, from double-scattering terms involving Pomeron exchange. This result agrees well with the two-pomeron contribution estimated by Donnachie and Landshoff [15]. At $\sqrt{s}=10$ GeV, the fitted pp cross section is 38.5 mb, with a contribution of 14.2 mb, or 37%, from double scattering. By comparison, the fitted $\pi^- p$ cross section at $\sqrt{s}=10$ GeV is 24.2 mb, with a contribution of 5.9 mb, or 24%, from double scattering. These values, while somewhat large, do not seem unreasonable. At high energy, double-scattering terms are thought to correspond to two-Pomeron exchange. As Donnachie and Landshoff have noted [15], two-Pomeron exchange is necessary to produce the dip seen in the differential cross section for pp elastic scattering, through interference with one-Pomeron exchange. We concur with their conclusion [12], based on the accuracy of their model, that single exchanges are dominant. We also concur with their view that asymptotic theorems, such as the Froissart bound, are not relevant at present energies [15].

Although the main aim of this paper is to discuss the importance of double-scattering contributions to hadronic total cross sections, it also seems worthwhile to discuss the total γp cross section within the same framework. From the usual quark wave functions for ρ° and ω mesons, it follows that

$$\sigma(\rho^\circ p)=\sigma(\omega p)=4.5S_u+1.5S_{\bar{u}}+8\,\delta_{uu}+0.5\delta_{\bar{u}\bar{u}}+6.5\delta_{\bar{u}u}. \tag{6}$$

Under the assumption of vector-meson dominance, we may write $\sigma(\gamma p)=\gamma_{\text{scale}}\sigma(\rho^\circ p)$, where γ_{scale} is taken as a constant scale factor. Table I gives fitted values of γ_{scale} when the γp cross-section measurements are included for fits 1 and 2; not surprisingly, the values agree well with each other. The values of X and Y obtained for fit 1 also agree reasonably well with the DL values, which are given in Table II. Figure 3 shows the fitted γp cross section using the parameters from our preferred fit, fit 2. As can be seen, this fit agrees quite well with recent results published by the H1 [16] and ZEUS [17] Collaborations at the DESY ep collider HERA. The H1 Collaboration found $\sigma(\gamma p)=(165\pm2\pm11)$

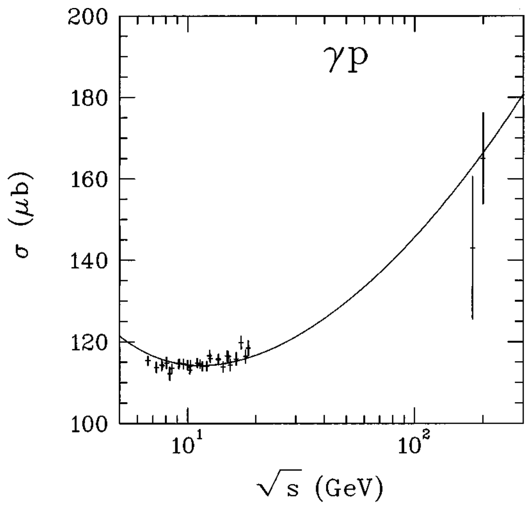

FIG. 3. Total cross-section data for γp. The curve is based on parameters from the second global fit discussed in the text.

μb at $\sqrt{s}=200$ GeV, and the ZEUS Collaboration found $\sigma(\gamma p)=(143\pm4\pm17)$ μb at $\sqrt{s}=180$ GeV. For comparison, at $\sqrt{s}=200$ GeV, the DL prediction is 160 μb, while our fit 1 gives $\sigma(\gamma p)=156$ μb, and fit 2 (our preferred fit, shown in Fig. 3) gives $\sigma(\gamma p)=166$ μb.

IV. SUMMARY AND CONCLUSIONS

At sufficiently high energies, Donnachie and Landshoff showed that all total hadronic cross sections can be efficiently parametrized by an energy-dependent form suggested by Regge theory [5]. The present work shows that a significant further reduction in the number of free parameters is made possible by using a parametrization suggested by the quark model. Our preferred global fit, with ten free parameters, may be used to make quantitative predictions of total cross sections for any baryon-baryon, meson-baryon, or meson-meson reactions. The success of our parametrization relies on recognizing the importance of double-scattering quark contributions at high energies.

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