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$\bar{p}p$ and pp Elastic Scattering from 10 GeV to 1000 GeV Centre-of-Mass Energy

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ABSTRACT

Antiproton-proton and proton-proton elastic scattering are studied simultaneously over the energy range $\sqrt{s} \approx 10 - 1000$ GeV in a nucleon valence core model proposed earlier. The scattering is described as primarily due to two processes: diffraction and hard scattering. The latter originates from the scattering of a nucleon core off another core. Destructive interference between the two processes produces dips in $\bar{p}p$ and pp differential cross sections. As energy increases beyond the ISR range ($\sqrt{s}=23-62$ GeV), the dips get filled up, and eventually transform into shoulders or breaks at collider energies. Differences between $\bar{p}p$ and pp differential cross sections persist even at collider energies. Comparison with ISR data show that the model provides a quantitative description of pp elastic scattering in this energy range. Predictions of $\bar{p}p$ and pp differential cross sections at future collider energies $\sqrt{s}=800$ and 2000 GeV are given. In order to distinguish between competing models, need for measuring the $\bar{p}p$ differential cross section at the ISR and SPS collider in the $|t|$ -range 0.5 to 2.0 GeV² is stressed.

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1. Introduction

Antiproton-proton elastic differential cross section has now been measured at the CERN SPS at incident momenta 50 and 30 GeV/c in the $|t|$ -region 0.5 to 6 GeV² [1,2]. The data show clear dip-bump structures with pronounced minima at $|t|=1.5$ GeV² for 50 GeV/c and at $|t|=1.7$ GeV² for 30 GeV/c. Preliminary results on $\bar{p}p$ elastic scattering from the CERN SPS collider [3] at the equivalent $p_{inc} \approx 155000$ GeV/c ($\sqrt{s}=540$ GeV) indicate only presence of a shoulder at $|t|=0.8$ GeV², and no pronounced dip. Proton-proton elastic scattering, as presently known, presents a somewhat different picture. Here a shoulder is seen at low energies ($p_{inc}=20-50$ GeV/c) [4,5], which gradually develops into a visible dip at 200 GeV/c [6,7] and becomes very pronounced at ISR energy $\sqrt{s}=30.5$ GeV ($p_{inc}=496$ GeV/c) [8]. Above that, with increasing energy the dip starts filling up while moving slowly to smaller $|t|$ values. Given this overall picture, one would like to see whether a consistent and unifying description of pp and $\bar{p}p$ elastic scattering can be obtained, and whether the underlying dominant mechanisms can be pinned down. Furthermore, since we expect at high energies particle and antiparticle scattering to be the same, one would like to gain insight as to how this asymptotic behaviour is approached, and how the leading C-odd contribution that distinguishes particle and antiparticle scattering falls off.

In this paper we report results of an investigation of pp and $\bar{p}p$ elastic scattering based on a model that indicates the existence of a nucleon core of valence quarks [9-11]. Our analysis extends from 30 GeV/c incident momentum through ISR energies ($\sqrt{s}=23-62$ GeV) to the highest presently accessible energy $\sqrt{s}=540$ GeV at the SPS collider. It also contains predictions for the elastic differential cross section at the Fermilab collider and at CBA in Brookhaven. We find a simple and coherent picture of pp and $\bar{p}p$ elastic scattering emerging. Previous study of the model [10] provided an overall quantitative picture of pp elastic scattering in the momentum range $p_{inc} \approx 15 - 1500$ GeV/c and over the momentum transfer interval $0 < |t| < 15$ GeV². In this study, we examine $\bar{p}p$ elastic scattering vis-a-vis pp elastic scattering, asymptotic energy dependence of these processes and the movement of the dip in pp and $\bar{p}p$ differential cross section as the c.m. energy $\sqrt{s}$ increases from 7.6 GeV to the collider value of 540 GeV.

2. Description of the Model

High energy pp elastic scattering in the present model [10] is primarily due to two processes: diffraction and hard scattering. Diffraction dominates the small momentum transfer region. The hard process is responsible for large $|t|$ scattering. The dip in pp arises from the destructive interference between the two processes. The hard scattering originates from the scattering of one nucleon core off the other via exchange of $u\bar{u}$ and $d\bar{d}$ pairs (in the vector meson state ω), while their outer hadronic clouds ($q\bar{q}$ sea) overlap and interact independently. The hard process is shown in Fig.1a in configuration space. In Fig.1b a momentum space diagram corresponding to the hard process is drawn, where the cloud-cloud interaction is approximated by a Regge pole.

The diffraction amplitude T_D and the hard amplitude T_H in the model are given by

$$T_D(s,t) = 2\pi p W N (R + i\pi a) H_0^{(1)} [q(R + i\pi a)] \quad (1a)$$

$$\approx 4 p W N \left(\frac{\pi R}{2q} \right)^{1/2} \exp \left[-q\pi a + i \left(qR - \frac{\pi}{4} + \frac{\varphi}{2} \right) \right]; \quad (1b)$$

$$T_H(s,t) = \eta(s) e^{i\zeta(s)} T_1(s,t), \quad (2) \quad (|t| = q^2)$$

$$T_1(s,t) = \gamma \left(\frac{s}{s_0} e^{-i\pi/2} \right)^{\alpha(0)} \frac{1}{(\ln(\frac{s}{s_0}))} \frac{F^2(t)}{m^2 - t}. \quad (3)$$

As seen above, diffraction is specified by three energy-dependent parameters: $R(s)$ (an interaction radius), $a(s)$ (a diffuseness length), $N(s)$ (an absorption parameter); $\mathcal{R} = (R^2 + \pi^2 a^2)^{1/2}$ and $\Phi = \arctan \pi a/R$. Approximation (1b) is valid for $8q\mathcal{R} \gg 1$. The hard amplitude T_H includes an absorption factor $\eta e^{i\zeta}$ due to diffraction. The form factor $F(t)$ represents the valence quark distribution as probed by the vector meson ω . $\alpha(0)$ is the intercept of the Regge trajectory shown in Fig.1b; m is the mass of the ω meson. The diffraction amplitude falls off exponentially in q : $T_D \sim e^{-q\pi a}$. The hard amplitude also falls off exponentially in q , because of the form factors: $F^2(t) \sim e^{-\beta q}$, where β is a length parameter indicating the finite size of the nucleon core.

The differential cross section for pp elastic scattering in the above model is given by

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt} \right)_D + \left(\frac{d\sigma}{dt} \right)_H - 2 \left(\frac{d\sigma}{dt} \right)_D^{1/2} \left(\frac{d\sigma}{dt} \right)_H^{1/2} \cos \left(qR(s) + \theta(s) \right), \quad (4)$$

where

$$\theta(s) = -\frac{\pi}{4} + \frac{\varphi(s)}{2} + \frac{\pi\alpha(0)}{2} - \zeta(s),$$

and $(d\sigma/dt)_D$, $(d\sigma/dt)_H$ are differential cross sections due to the diffraction amplitude and the hard amplitude alone. The last term represents the interference contribution.

To study $\bar{p}p$ elastic scattering in this model, the first step is to change the sign of the interference term in Eq.(4). The reason is that the exchanged particle in the hard interaction is an ω , which has an odd charge conjugation, while the associated cloud-cloud interaction should be C-even.² Hence the overall C for the hard amplitude has to be odd. We now quantitatively study the consequence of this conclusion for $\bar{p}p$ elastic scattering at 50 GeV/c and 30 GeV/c.

3. $\bar{p}p$ Elastic Scattering at 50 and 30 GeV/c

First we fit the pp elastic scattering data at 50 GeV/c [5] in the framework of this model with a set of diffraction parameters a , R , N and hard parameters $\alpha(0)$, γ . Our quantitative fit is shown in Fig.2a. If we now keep for $\bar{p}p$ the same set of diffraction and hard scattering parameters as for pp , then the interference term in the dip region, which is destructive for pp , becomes constructive for $\bar{p}p$. Consequently, we expect a bump in $\bar{p}p$ at $t = -1.4 \text{ GeV}^2$. Clearly, the $\bar{p}p$ elastic data (Fig.2b) do not show that kind of behaviour.

Diffraction, however, is different for $\bar{p}p$ and pp at these energies (total cross sections and diffraction slopes for $\bar{p}p$ and pp at 50 GeV/c are experimentally known to be different [12]). Without changing the hard scattering parameters, the question is then: Is it possible to find a set of diffraction parameters (a, R, N) that reproduces the $\bar{p}p$ data? Computer search has yielded us the angular distribution shown by the dashed curve in Fig.2b. The overall behaviour of the differential cross section, the dip-bump structure and the cross sections at large $|t|$ are well reproduced. The position of the dip agrees perfectly with the data. However, the quantitative agreement for $\bar{p}p$ (Fig.2b) is not as good as in pp (Fig.2a). We attribute this to the presence of many annihilation channels in $\bar{p}p$ and to the possibility that, because of the low c.m. energy, the cloud-cloud interaction in Fig.1 is not 100% C-even.³ As in

² In a quark model description of this hard process, the quantum numbers are being carried by the valence quarks, and the outer cloud in Fig.1b has to be $q\bar{q}$ sea. Since the sea carries no quantum numbers, the interaction between the two seas should be C-even.

³ In an earlier investigation, we showed that if a C-odd component is allowed in the cloud-cloud interaction, then a satisfactory quantitative fit of the

pp, the dip originates from a destructive interference between the diffraction and the hard amplitude. However, there is a major difference. To reproduce the observed dip-bump structure, we had to introduce an interaction radius $R_{\bar{p}p} = 7.70 \text{ GeV}^{-1}$, which is large compared to $R_{pp} = 4.68 \text{ GeV}^{-1}$. In pp the observed dip corresponds to the first destructive interference ($qR_{pp} + \theta_{pp} \approx 2\pi$) between the diffraction and the hard amplitude. In contrast, what we are finding in $\bar{p}p$ is that the large interaction radius here brings the first constructive interference toward the origin, and the $\bar{p}p$ dip corresponds to the second destructive interference ($qR_{\bar{p}p} + \theta_{\bar{p}p} \approx 3\pi$).⁴

Recently $\bar{p}p$ elastic scattering at 30 GeV/c has been measured [2], which shows again a clear dip-bump structure with a dip at $|t| \approx 1.7 \text{ GeV}^2$. An analysis of the data can be carried out as for 50 GeV/c. We first fit pp elastic data at 30 GeV/c [13] as shown in Fig.3a, determine the hard scattering parameters $\alpha(0)$ and γ , and then use them for $\bar{p}p$ scattering. We next search for a suitable set of diffraction parameters to describe the observed $\bar{p}p$ differential cross section. The angular distribution obtained from such an analysis is shown in Fig.3b. As before, the overall behaviour of $d\sigma/dt$ including the dip-bump structure and the position of the dip are well reproduced.⁵ We conclude: (1) $\bar{p}p$ elastic scattering at 50 and 30 GeV/c can be satisfactorily described by the diffraction plus hard scattering model; and (2) the hard scattering parameters as determined by pp scattering can reproduce large $|t|$ cross sections for $\bar{p}p$ scattering.

The next question to face is then: Can the model provide a unifying description of high energy pp and $\bar{p}p$ elastic scattering? In particular, how do they approach each other asymptotically as s increases, and what differences can be observed between pp and $\bar{p}p$ at present energies? Answer to this question, of course, requires an understanding of the energy dependence of the parameters in the model. This we now examine.

50 GeV/c $\bar{p}p$ elastic data can be obtained (M.M. Islam and J.P. Guillaud, Univ. of Connecticut Preprint (1980), unpublished)

⁴ The first destructive interference: $qR_{\bar{p}p} + \theta_{\bar{p}p} \approx \pi$ corresponds to very small value of $|t|$, where diffraction predominates.

⁵ That the dip should move to higher $|t|$ -value when energy is decreased from 50 GeV/c was indicated in our earlier preprint (see footnote 3).

4. Energy Dependence of Parameters

Hard scattering is described by five parameters in our model. Of these, three (β, m, s_0) are energy independent and kept fixed at the values found in the earlier investigation [10]. The other two, $\alpha(0)$ and γ , correspond to the intercept and the coupling of an effective Regge trajectory that represents the cloud-cloud interaction (Fig.1b). It was also pointed out that as the energy increases, $\alpha(0)$ should become 1 corresponding to the Pomeron exchange. Thus, we envisage a slow increase of $\alpha(0)$ from the value 0.863 found earlier to 1.0 as we extend the model to higher energies. In principle, this can be accompanied by a slow variation of the effective coupling strength γ (in fact, we find a constant value of $\gamma = -14.0$ satisfactory from $p_{inc}=50$ GeV/c to the SPS collider energy). With regard to the energy dependence of the diffraction parameters, we use for pp

$$a(s) = a_0 + a_1 \ln s, \quad R(s) = R_0 + R_1 \ln s, \quad N(s) = N_0 + N_1 \ln s, \quad (5a)$$

and for $\bar{p}p$

$$\bar{a}(s) = \bar{a}_0 + \bar{a}_1 \ln s, \quad \bar{R}(s) = \bar{R}_0 + \bar{R}_1 \ln s, \quad \bar{N}(s) = \bar{N}_0 + \bar{N}_1 \ln s; \quad (5b)$$

(s in units of 1 GeV²)

The above parametrization for diffraction parameters is based on the following considerations:

1. From the Pomeranchuk-type theorem of Cornille and Martin [14], we expect pp and $\bar{p}p$ differential cross sections to be the same within the diffraction peak as $s \rightarrow \infty$. The coefficients of $\ln s$ terms in (5a) and (5b) are identical; this leads to the same value of a, R, N for pp and $\bar{p}p$ as $s \rightarrow \infty$. Hence, asymptotically pp and $\bar{p}p$ diffraction scattering are going to be the same in our model.

2. It has been shown by Auberson, Kinoshita and Martin [15] that scattering amplitudes, which saturate the Froissart bound, have for $s \rightarrow \infty$ impact parameter representations, and the b-dependence of the impact parameter amplitudes is scaled by $\ln s$:

$$\frac{e^{i\chi(s,b)} - 1}{2i} \sim f\left(\frac{b^2}{(\ln s)^2}\right). \quad (6)$$

We see that the parametrization (5) does, in fact, ensure this asymptotic scaling behaviour for our diffraction profile:

$$\frac{e^{i\chi_D(s,b)} - 1}{2i} = - \frac{2i N(s) (R(s) + i\pi a(s))}{b^2 - (R(s) + i\pi a(s))^2} \quad (7a)$$

$$\underset{s \rightarrow \infty}{\simeq} - \frac{2i N_1 (R_1 + i\pi a_1)}{\frac{b^2}{(\ln s)^2} - (R_1 + i\pi a_1)^2} \quad (7b)$$

In the context of the above discussion, two points need to be clarified:

a) We should distinguish between the asymptotic geometrical scaling of Auberson et al. (Eq.6) and the phenomenological geometrical scaling of Dias de Deus [16]. In the latter case, the b -dependence is scaled by $\sqrt{\sigma_T(s)}$:

$$\frac{e^{i\chi(s,b)} - 1}{2i} \sim f\left(\frac{b^2}{\sigma_T(s)}\right) \quad (8)$$

above some value of s . This scaling is assumed to set in, say, at ISR energies, where $\sigma_T(s)$ is not very far from its low energy value. Phenomenological geometrical scaling will coincide with the asymptotic geometrical scaling only when the energy is so high that $\sigma_T(s) \propto (\ln s)^2$.

b) Auberson et al. [15] have also proven that:

$$T(s,t) \underset{s \rightarrow \infty}{\sim} s (\ln s)^2 f(q^2 \ln^2 s), \quad (q^2 = -t) \quad (9)$$

where $f(\tau)$, $\tau = q^2 \ln^2 s$, is an entire function of τ bounded by $e^{c\sqrt{|\tau|}}$. In our case, from the asymptotic profile function (7b), we obtain

$$T_D(s,t) \simeq \pi s (\ln s)^2 N_1 (R_1 + i\pi a_1) H_0^{(1)}[q \ln s (R_1 + i\pi a_1)]. \quad (10)$$

The Hankel function $H_0^{(1)}[\sqrt{\tau}(R_1 + i\pi a_1)]$ is not an entire function of $\tau = q^2 \ln^2 s$. It has a cut from $\tau=0$ to $+\infty$. The origin of this behaviour lies in our profile function (7a), which does not fall off fast enough for large b . In fact, this leads to a singular amplitude in the forward direction. There is, however, no basic problem involved here. The effective maximum angular momentum $L_{\max}$ corresponding to the Froissart-Martin bound is known to be $c\sqrt{s} \ln s$ [17]. Therefore, in the impact parameter representation of $T_D(s,t)$, $c \ln s = L_{\max}/p$ provides a natural cut-off. And if this cut-off is applied, $T_D(s,t)$ becomes an entire function of $q^2 \ln^2 s$. For $q \neq 0$, the upper limit of the integral over b can be extended to infinity, since only small values of b are involved, and the result (10) comes out. As our primary interest lies in seeing how diffraction and

hard scattering compete with each other, and therefore in the differential cross section away from the forward direction, our calculations are not affected by the singularity of $T_D(s,t)$ at $t=0$.

5. Quantitative Study of pp and $\bar{p}p$ Scattering and Predictions

Our investigation shows that pp is surprisingly quite asymptotic. If the diffraction parameters $a(s)$, $R(s)$, $N(s)$ for pp scattering are determined at two energies, say, at $p_{inc}=50$ GeV/c and 1486 GeV/c ($\sqrt{s}=52.8$ GeV), then from (5a) we can determine these parameters at any other energy. We can, therefore, predict pp differential cross sections at energies we want (allowing, of course, for small increase of $\alpha(0)$ with energy). The result of such an analysis is shown in Fig.4, where the calculated cross sections at $\sqrt{s}=23.4$, 30.5, 44.6 and 62.1 GeV are compared with the ISR data [8].⁶ The agreement is excellent, indicating (i) that the pp diffraction amplitude follows the asymptotic energy dependence (5a) quite well, (ii) that the model provides a remarkably good description of pp elastic scattering from 50 GeV/c to 2000 GeV/c with respect to the t-dependence as well as the s-dependence.⁷

To investigate $\bar{p}p$ scattering, we need first a set of diffraction parameters at high energy that would determine $\bar{a}_0, \bar{R}_0, \bar{N}_0$ in (5b). This led us to examine the preliminary $\bar{p}p$ collider data of the UA4 group at $\sqrt{s}=540$ GeV [3]. From computer search we found that an adequate fit to the data could be obtained on the basis of our model (Fig.5).⁸ The fit provides us with a set of a , R , N for $\bar{p}p$ at this energy. Extrapolating this set to $p_{inc}=50$ and 30 GeV/c, we find values of a and R that are appreciably different from the ones given by our actual fits (Figs.2b and 3b). This shows that, unlike pp, the $\bar{p}p$ diffraction amplitude is not yet asymptotic in the region $p_{inc}\approx 50 - 2000$ GeV/c. However, what we also find is that knowing the parameters asymptotically and at 30 GeV/c and 50 GeV/c, we can interpolate them quite well by either graphical or analytic method. We are thus able to predict $\bar{p}p$ differential cross sections in the ISR range and beyond, and compare them with pp scattering. The result of this investigation is shown in Fig.6, where $\bar{p}p$ differential cross sections calculated

⁶ Values of the diffraction parameters are given in Table 1.

⁷ This corroborates previous quantitative study of the model [10], where the diffraction parameters were taken to vary with energy, but no systematic energy dependence was explored.

⁸ Hard scattering parameters in this case are essentially fixed, with $|\gamma|$ having the ISR value 14.0 GeV^2 , and $\alpha(0)=1.0$.

at $\sqrt{s}=23.4, 30.5, 52.8, 200$ and 400 GeV are given together with the calculated pp cross sections. We see that there are distinct dips in the $\bar{p}p$ differential cross sections at these energies, and they occur at smaller $|t|$ values than the pp dips. Experimental verification of these dips would be very important from our point of view. From the calculated differential cross sections, we can also obtain the local slope parameter $b(s,t)=d/dt[\ln(d\sigma/dt)]$. For $|t|=0.4$ GeV² and $\sqrt{s}=31, 53$ and 62 GeV, we find $b^{\bar{p}p}(s,t)=10.14, 10.35$ and 10.54 , respectively. These values are in agreement with the preliminary ISR $\bar{p}p$ experimental results [18].

To see how pp compares with $\bar{p}p$ at SPS collider energy, where the asymptotic behaviour (5b) has also set in for $\bar{p}p$, we show in Fig.7 the calculated pp differential cross section and our fit of the preliminary $\bar{p}p$ collider data. (Also shown for comparison are ISR pp data at $\sqrt{s}=53$ GeV). We see that the pp differential cross section looks very much like that of $\bar{p}p$. The pp dip has disappeared. Instead, a shoulder (or break) has formed just like $\bar{p}p$, but the position of the pp shoulder is at higher $|t|$ than that of the $\bar{p}p$ shoulder. Quantitative predictions of pp and $\bar{p}p$ differential cross sections at future collider energies $\sqrt{s}=800$ GeV (CBA in Brookhaven) and $\sqrt{s}=2000$ GeV (Fermilab) are also given in Fig.7.⁶ We observe from the curves that differences between pp and $\bar{p}p$ persist even at these superhigh energies, and that the differential cross sections at large $|t|$ are nearly equal to the ISR cross sections.

The calculated angular distributions in Figs.6 and 7 also show that the pp and $\bar{p}p$ dips gradually fill up, while moving towards smaller $|t|$ values, and finally transform into shoulders or breaks. Tracing the development of the $\bar{p}p$ dip from $p_{inc}=30$ GeV/c upwards, we then come to the conclusion that the $\bar{p}p$ dip at 50 GeV/c, seen by Asa'd et al.[1], transforms into the $\bar{p}p$ shoulder at collider energy, seen by the CERN UA4 group [3].

6. Comparison with other Models

A number of models have been proposed to describe high energy pp and $\bar{p}p$ elastic scattering, and it is of interest to compare them briefly with ours. In the geometrical model of Chou and Yang [19], pp and $\bar{p}p$ elastic scattering are described in the same way. The difference in pp and $\bar{p}p$ angular distributions at the same energy originates in this model from the difference in their total cross sections. Like the pp dip at ISR energies, the observed dip in $\bar{p}p$ elastic scattering at $|t|\approx 1.5$ GeV² for 50 GeV/c incident momentum is interpreted as due to the cancellation between the single and the double scattering terms. Furthermore, this dip is associated with the low energy $\bar{p}p$ structure in the region $0.5-0.8$ GeV². The model then predicts a $\bar{p}p$ dip at $|t|\approx 1.1$ GeV² for

30 GeV/c incident momentum [20]. The recent measurement [2] of the $\bar{p}p$ differential cross section at this momentum shows a prominent dip at $|t| \approx 1.7 \text{ GeV}^2$; that is, at a higher value of $|t|$ than the $\bar{p}p$ dip at 50 GeV/c. This indicates that the actual mechanism producing pp and $\bar{p}p$ dips is different from that suggested by the Chou-Yang model. For $\bar{p}p$ elastic scattering at SPS collider energy, where the measured total cross section is $66 \pm 7 \text{ mb}$ [21], the geometrical model predicts a sharp dip at $|t| \approx 0.75 \text{ GeV}^2$ followed by a second maximum at $|t| \approx 1.0 \text{ GeV}^2$. Preliminary results of the CERN UA4 experiment [3] show no dip; instead data show a distinct shoulder in the differential cross section beginning at $|t| \approx 0.8 \text{ GeV}^2$. If these results are further confirmed, then the Chou-Yang geometrical model has to be ruled out.

In the geometrical scaling model of Dias de Deus and Kroll [22], the dip in pp elastic scattering originates from a zero in the imaginary part of the scattering amplitude. This in turn occurs because of a zero in their scaling function $\Phi(\tau)$, where $\text{Im}T(s,t) = \text{Im}T(s,0)\Phi(\tau)$, and τ is the scaling variable $-\tau\sigma_T$. $\bar{p}p$ elastic scattering is described by the same function $\Phi(\tau)$, so that one predicts a dip in $\bar{p}p$ scattering at

$$t_{\min}^{\bar{p}p} = t_{\min}^{pp} \frac{\sigma_T^{pp}}{\sigma_T^{\bar{p}p}}$$

Since $\sigma_T^{\bar{p}p} > \sigma_T^{pp}$ at ISR energies, this predicts a $\bar{p}p$ dip at a somewhat smaller $|t|$ than for pp in this energy region. The dip is partially filled by the real part of the amplitude, which is given by

$$\text{Re} T(s,t) = \text{Im} T(s,0) \rho(s) \frac{d}{d\tau} [\tau \Phi(\tau)] \quad , \quad \rho(s) = \frac{\text{Re} T(s,0)}{\text{Im} T(s,0)}$$

The function $\Phi(\tau)$ has been determined numerically from the ISR pp data at $\sqrt{s} = 53 \text{ GeV}$. Therefore, given σ_T and ρ at any energy, the model can predict pp and $\bar{p}p$ differential cross sections. In this model, $\sigma_T^{\bar{p}p}$ and σ_T^{pp} as well as $\rho^{\bar{p}p}$ and ρ^{pp} should approach each other rapidly (as there is no important C-odd exchange around). Therefore, at collider energies one expects differential cross sections of pp and $\bar{p}p$ to coincide, in contrast to our prediction (Fig.7). The geometrical scaling model, of course, correctly predicted a shoulder instead of a dip in $d\sigma/dt$ at collider energy [22], based on the argument that the large real part at this energy fills up the dip. Quantitative verification of the model with $\bar{p}p$ experimental results at ISR and collider energies remains to be seen. We should add that from the Cornille-Martin theorem [14] on the equality of particle-particle and particle-antiparticle differential cross sections, one expects

$$\frac{d\sigma^{\bar{p}p}(s,t(s))}{dt} \bigg/ \frac{d\sigma^{pp}(s,t(s))}{dt} \rightarrow 1$$

as $s \rightarrow \infty$ for t -values within the diffraction peak.⁹ If the dip in pp belongs to the diffraction peak, then $\bar{p}p$ will have the same dip essentially at the same position.

Donnachie and Landshoff [23] have proposed a model of high energy pp and $\bar{p}p$ elastic scattering based primarily on three processes: (i) single Pomeron exchange, (ii) double Pomeron exchange, and (iii) triple gluon exchange. The prominent dip in the pp differential cross section is produced by the cancellation of the imaginary part of the single Pomeron exchange by that of the double Pomeron exchange, while the substantial real part of the single Pomeron exchange is cancelled by the triple gluon exchange. Since the triple gluon exchange changes sign in $\bar{p}p$ scattering, this model predicts, in contrast to ours and the geometrical scaling model, no dips in the $\bar{p}p$ differential cross section at ISR energies - only shoulders. At collider energies, the model predicts shoulders for $\bar{p}p$ and prominent dips for pp . Furthermore, to explain dips in low energy $\bar{p}p$ elastic scattering, Donnachie and Landshoff invoke an added mechanism, namely, contributions from Regge-Pomeron exchanges. In this model, therefore, the $\bar{p}p$ dip at low energies has a different origin than the pp dip at ISR energies, and the $\bar{p}p$ dip should disappear fast as the energy increases, in contrast to the predictions of the geometrical scaling model [22] and our model. $\bar{p}p$ elastic scattering data at ISR and SPS in the region $|t|=0.5-2.0 \text{ GeV}^2$ will be crucial to decide this issue.

7. Concluding Remarks

A number of points emerge from this investigation within the framework of the model:

1. pp and $\bar{p}p$ large momentum transfer scattering ($|t|$ beyond second maximum) originate from the same hard mechanism, and are described quantitatively by the same set of hard parameters.¹⁰

2. The dip in pp and $\bar{p}p$ arises from the destructive interference between the diffraction amplitude and the C-odd hard scattering amplitude.

⁹ These values are defined by the condition that the ratio $d\sigma/dt(s,0) / d\sigma/dt(s,t(s))$ remains finite when $s \rightarrow \infty$ [14].

¹⁰ The multiplicative absorption factor $e^{iX(s,0)}$ in Eq.2 is, of course, different for pp and $\bar{p}p$, since diffraction is different for the two processes.

3. As energy increases, the diffraction peaks in $\bar{p}p$ and pp shrink, and the position in $|t|$ where diffraction and hard amplitudes are equal in magnitude, moves toward smaller values -- away from the position where the relative phase corresponds to maximum destructive interference (this latter position is given by $qR(s)+\theta(s)=2\pi$ for pp , and 3π for $\bar{p}p$). As a result, the dips in pp and $\bar{p}p$ gradually fill up and develop into shoulders.

4. For a given fixed momentum transfer $|t|$, as s becomes large, the hard $C=-1$ amplitude dominates. This is because from Eqs.(1b) and (5),

$$|T_D(s,t)| \sim s (\ln s)^{3/2} \frac{e^{-q\pi a_0}}{(q_V)^{1/2} s^{q\pi a_1}}, \quad (11)$$

while from Eqs.(2) and (3), since $\eta(s) \rightarrow \text{const}$ as $s \rightarrow \infty$,

$$|T_H(s,t)| \sim \frac{s}{\ln s} \frac{F^2(-q^2)}{m^2 + q^2}. \quad (12)$$

The $s^{q\pi a_1}$ factor in the denominator of Eq.(11) shows that the diffraction peak shrinks indefinitely for fixed $|t|$, thereby exposing the C-odd hard amplitude (Eq.12).

However, for $s \rightarrow \infty$ and $t = t(s) = C/\ln^2 s$, we get from Eq.(10) or Eqs.(1a) and (5),

$$|T_D(s,t)| \sim s (\ln s)^2,$$

whereas, from Eqs.(2) and (3), we have

$$|T_H(s,t)| \sim \frac{s}{\ln s};$$

therefore, diffraction dominates, and

$$\frac{d\sigma^{\bar{p}p}}{dt}(s,t(s)) / \frac{d\sigma^{pp}}{dt}(s,t(s)) \rightarrow 1 \quad (13)$$

as required by the Cornille-Martin theorem [14]. In our model, equality of $\bar{p}p$ and pp differential cross sections also holds for $s \rightarrow \infty$ and $|t|$ fixed, because $|T_H^{\bar{p}p}(s,t)|/|T_H^{pp}(s,t)| \rightarrow 1$ in this limit.

5. The factor of s in Eq.(12) that makes the hard scattering so important at high energies, arises from the diffraction scattering between the clouds of the colliding particles. For fixed $|t|$ and sufficiently large s , this amplitude overpowers the diffraction amplitude, and its contribution appears as a distinct shoulder in $\bar{p}p$ differential cross section at the collider energy.

6. The slope parameter $b_D(s,t)=d/dt[\ln(d\sigma/dt)_D]$ for the diffraction scattering can be explicitly calculated using Eq.(1b). It is given by

$$\begin{aligned} b_D(s,t) &= \frac{\pi a(s)}{q} + \frac{1}{2q^2} \\ &= \frac{\pi a_0}{q} + \frac{1}{2q^2} + \frac{\pi a_1}{q} \ln s \end{aligned} \quad (14)$$

The coefficient $\pi a_1/q$ of the $\ln s$ term has the value 0.31 GeV^{-2} for $q^2=0.4 \text{ GeV}^2$, which is in reasonable agreement with experimental results [24].¹¹ Eq.(14) predicts a finite difference between $\bar{p}p$ and pp diffraction slopes at fixed $|t|$:

$$b_D^{\bar{p}p}(s,t) - b_D^{pp}(s,t) = \frac{\pi}{q} (\bar{a}_0 - a_0) ; \quad (15)$$

however, $b_D^{\bar{p}p}(s,t)/b_D^{pp}(s,t) \rightarrow 1$ as $s \rightarrow \infty$.

We also note: (i) Eq.(14) predicts a t -dependence of the diffraction peak; (ii) $b(s,t) \approx \pi a_1 \ln s / q$ ($s \rightarrow \infty$) saturates the bound on diffraction slope [25] for fixed $|t|$ ($q=\sqrt{|t|}$).

We conclude that pp and $\bar{p}p$ elastic scattering at high energy allow a simple and unifying description; namely, that the scattering is due to two basic mechanisms: diffraction and hard scattering. These two processes interfere destructively producing dips, which become shoulders or breaks at collider energies. The hard scattering arises from the scattering of a nucleon valence core off the other core. In our opinion, the model has survived well the present analysis. We obtain a very consistent agreement with pp data for incident momentum $30 \text{ GeV}/c$ to $2056 \text{ GeV}/c$ and also with preliminary $\bar{p}p$ data from ISR and the SPS collider. If the predictions of the model are borne out by future collider experiments, then the existence of a nucleon valence core will be undoubtedly established.

¹¹ We like to thank J.P. Martin for a discussion on this point.

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References

- [1] Z. Asa'd et al., Phys.Lett.108B (1982) 51.
- [2] T. Fearnley, Contribution to the International Europhysics Conference on High Energy Physics, Brighton (July 1983): Annecy-CERN-Copenhagen-Oslo-Genova-London(UC) Collaboration
- [3] J. Timmermans, XVIII Rencontre de Moriond (March, 1983).
M. Bozzo et al., Contribution to the International Europhysics Conference on High Energy Physics, Brighton (July 1983).
- [4] J.V. Allaby et al., Nucl.Phys.B52 (1973) 316.
- [5] Z. Asa'd et al., CERN-EP/83-68 (to be published in Phys.Lett.B).
- [6] G. Fidecaro et al., Phys.Lett.105B (1981) 309.
D.H. Kaplan et al., Phys.Rev.D26 (1982) 723.
- [7] R. Rusack et al., Phys.Rev.Lett.41 (1978) 1632.
- [8] E. Nagy et al., Nucl.Phys.B150 (1979) 221.
- [9] M.M. Islam, Lett. Nuovo Cimento 14 (1975) 627.
- [10] G.W. Heines and M.M. Islam, Nuovo Cimento 61A (1981) 149.
- [11] G. Alberi and G. Goggi, Phys.Reports 74 (1981) 1.
- [12] A.S. Carroll et al., Phys.Rev.Lett.33 (1974) 928.
Fermilab Single Arm Spectrometer Group, Phys.Rev.Lett.35 (1975) 1195.
- [13] R.M. Edelstein et al., Phys.Rev.D5 (1972) 1073.
G. Cocconi et al., Phys.Rev.B138 (1965) 165.
- [14] A. Martin, Zeit.Phys.C15 (1982) 185.
- [15] G. Auberson, T. Kinoshita and A. Martin, Phys.Rev.D3 (1971) 3185.
- [16] J. Dias de Deus, Nucl.Phys.B59 (1973) 231.
A.J. Buras and J. Dias de Deus, Nucl.Phys.B71 (1974) 481.
- [17] S.M. Roy, Phys.Reports 5 (1972) 125.
- [18] F. Fabbri, XVIIIth Rencontre de Moriond (January, 1983): Ames-Bologna-CERN-Dortmund-Heidelberg-Warsaw Collaboration.
- [19] T.T. Chou and C.N. Yang, Phys.Rev.D19 (1979) 3268.
- [20] T.T. Chou and C.N. Yang, Phys.Rev.Lett.46 (1981) 764.
- [21] M. Haguenaer, 21st Int. Conf. on High Energy Physics, Paris 1982, (edited by P. Petiau and M. Porneuf), page C3-579.
- [22] J. Dias de Deus and P. Kroll, Acta Physica Polonica B9 (1978) 157.
J. Dias de Deus and P. Kroll, J.Phys.G 9 (1983) L81.
- [23] A. Donnachie and P.V. Landshoff, Univ. of Cambridge preprint (DAMTP 83/9).
A. Donnachie and P.V. Landshoff, Phys.Lett.123B (1983) 345.
- [24] J.P. Burq et al., Nucl.Phys.B217 (1983) 285.
- [25] A. Martin, CERN Preprint, TH.3527 (1983).

Figure Captions

- Fig.1 a) Physical picture of the hard scattering process: the nucleon cores scatter off one another via ω exchange, while their outer hadronic clouds ($q\bar{q}$ sea) overlap and interact independently.
 b) Momentum space diagram corresponding to the hard process: The valence quarks forming the nucleon cores interact via $u\bar{u}$ and $d\bar{d}$ pairs (in the vector meson state ω), while the $q\bar{q}$ seas (dashed lines) interact via Regge pole exchange (wavy line).

- Fig.2 a) Solid line is a fit of the 50 GeV/c pp data of Asa'd et al. [5]. Values of the parameters are: $a=1.60 \text{ GeV}^{-1}$, $R=4.68 \text{ GeV}^{-1}$, $N=0.70 \text{ GeV}^{-1}$; $\alpha(0)=0.863$, $|\gamma|=14.0 \text{ GeV}^2$.
 b) Dashed line is the calculated differential cross section for $\bar{p}p$ at 50 GeV/c for the set of parameters $a=1.80$, $R=7.70$, $N=1.80$; $\alpha(0)$ and $|\gamma|$ are the same as in Fig.2a. $\bar{p}p$ experimental data are from Asa'd et al. [1].

- Fig.3 a) Solid line is a fit of the 30 GeV/c pp data of Edelstein et al. [13]. Values of the parameters are: $a=1.57$, $R=4.65$, $N=0.66$; $\alpha(0)=0.863$, $|\gamma|=19.5$.
 b) Dashed line represents calculated $\bar{p}p$ differential cross section at 30 GeV/c for the set of parameters: $a=1.65$, $R=7.25$, $N=1.76$; $\alpha(0)$ and $|\gamma|$ are the same as in Fig.3a. The $\bar{p}p$ 30 GeV/c experimental data are from Ref. [2].

- Fig.4 Solid line for $\sqrt{s}=52.8 \text{ GeV}$ is a fit of the experimental data. Other solid lines represent predicted differential cross sections (with small variation of $\alpha(0)$). Experimental points are the ISR pp data of Nagy et al. [8].

- Fig.5 Solid line represents our fit of the preliminary $\bar{p}p$ collider data of the CERN UA4 group [3]. The $\bar{p}p$ diffraction parameters obtained are: $a=2.55$, $R=9.30$, $N=2.44$. ISR pp data at $\sqrt{s}=53 \text{ GeV}$ for small as well as for large $|t|$ are shown for comparison (data from K.R. Schubert, compilation in Landolt-Bornstein, Neue Serie vol.1 9, 1980).

- Fig.6 Calculated $\bar{p}p$ differential cross sections (dashed lines) at energies $\sqrt{s}=23.4, 30.5, 52.8, 200$ and 400 GeV , compared with the calculated pp differential cross sections (solid lines). Dips in $\bar{p}p$ cross sections similar to pp ones are predicted.

- Fig.7 Elastic differential cross sections for pp (solid lines) and

$\bar{p}p$ (dashed lines) at collider energies $\sqrt{s}=540$ GeV (CERN SPS), 800 GeV (Brookhaven CBA) and 2000 GeV (Fermilab). ISR pp elastic data at $\sqrt{s}=52.8$ GeV [8] are shown for comparison. The $\bar{p}p$ curve for $\sqrt{s}=540$ GeV is a fit to the preliminary UA4 data. All other curves are predicted differential cross sections. For all curves $\alpha(0)=1.0$, $|\gamma|=14.0$ GeV².

Table 1: Diffraction parameters for pp and $\bar{p}p$ (see Eq.5)

	a_0	a_1	R_0	R_1	N_0	N_1
pp	1.317	6.21×10^{-2}	4.439	5.18×10^{-2}	0.336	7.99×10^{-2}
$\bar{p}p$	1.769	"	8.648	"	1.435	"

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig.6

Fig. 7