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SEMI-TRANSPARENT HADRONS FROM MULTI-CHANNEL ABSORPTION EFFECTS

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ABSTRACT

We analyze the absorption structure of diffractive dissociation discussing simultaneously the elastic and inelastic processes. This approach is motivated by their close interdependence and mutual influence. We show that the results differ significantly from the standard picture of elastic scattering. In particular, protons are shown to have very rich internal structure coupling both to "black" and "transparent" diffractive scattering eigenstates. Proton matter distribution may well be very different from that suggested by the analysis of Chou and Yang. Finally, the indicated asymptotic behaviour is that of a "grey" instead of a "black" disc limit.

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1. INTRODUCTION

Recently, important progress has been achieved in the understanding of the cut structure of Pomeron exchange amplitude. It has been shown by Blankenbecler ¹⁾ that in a quite general Feynman diagram model, the opening of diffractive inelastic channels leads to a decrease in the total cross-section. Another important and closely related result has been derived by Pumplin ²⁾ [see also Ref. 3)]. These authors have shown that the s channel unitarity and the assumption that the inelastic, as well as the elastic diffraction is the shadow of non-diffractive particle production imply the following bound:

$$\sigma_e(b) + \sigma_{\text{diff}}(b) \leq \frac{1}{2} \sigma_{\text{tot}}(b) \quad (1)$$

Here, $\sigma_i(b) = (1/2)d\sigma_i/db^2$, where $i = \text{el, diff, tot}$, is the elastic, inelastic diffractive and total cross-section, respectively, in a collision at impact parameter b . This bound was applied to high-energy proton-proton scattering by Caneschi et al. ⁴⁾. Among other results, it was found that the bound, supplemented by the experimental information about the size of total inelastic diffractive cross-section, implies that the inelastic diffraction is peripheral in impact parameter space. The peripherality of inelastic diffraction had previously been strongly suggested by phenomenological analyses of data ⁵⁾. Its origin, however, was not well understood.

In this note we wish to point out several other important consequences of the absorption scheme mentioned above. We have three points to make. The first one concerns the size of σ_{diff} . Experiments carried out at high energy have shown σ_{diff} to be about 6 to 8 mb. Should this be regarded as a small or as a large value? Many authors, inspired by the observation that $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ is about 0.2 ($\ll 1$), have argued that σ_{diff} is small and its contribution into the unitarity sum of the elastic amplitude may be treated as a small perturbation. We argue that the experimentally observed size of σ_{diff} should be regarded as extremely large and that this standard approach may give a very distorted picture of the structure of the elastic amplitude. This point, of course, was implicit already in Ref. 4). Here we demonstrate it in a way which, we hope, is more illustrative. We carry out an analysis of the spectrum of the diffractive eigenamplitudes that contribute to proton-proton scattering and show that the opacities of these amplitudes vary over a very large range. We discuss the possible interpretation of this effect.

The two other points we wish to make are immediate corollaries of the above one. We show that eikonal model analyses of elastic scattering, in which the effects of inelastic diffractive channels are included ^{*}), give results drastically different from those of the standard analyses, in which such effects are neglected. In particular, we take the point of view that the applications of the Chou and Yang eikonal model ⁶⁾ believed to be rather successful ⁷⁾ should be regarded as misleading and their success as accidental. We discuss the energy dependence of the b space profile of elastic scattering and interpret the observed approximate "geometric scaling" ⁸⁾ as being due to the nearly saturated "effective unitarity bound" caused by the presence of inelastic diffractive channels and lying below the real upper unitarity bound. Finally, we speculate about the asymptotic behaviour of the elastic amplitude, and suggest that in the high-energy limit hadrons are not black but semi-transparent expanding discs.

2. THE SPECTRUM OF DIFFRACTIVE EIGENAMPLITUDES

Following Refs. 2) and 4), we label the states produced in diffractive pp interactions by $|1\rangle$ (elastic state), $|2\rangle$, ..., $|N\rangle$, and the non-diffractively produced states by $|N+1\rangle$, We discuss the $\tilde{t}$ matrix defined by

$$S \equiv 1 + iT \equiv 1 - \tilde{t} \quad (2)$$

where S is the scattering matrix. Our labelling defines within the $\tilde{t}$ matrix, the $N \times N$ "diffractive" submatrix t whose elements describe the transitions between the physical diffractive states. We assume that the diffractive amplitudes T_{ij} ($i, j = 1 \dots N$) are imaginary and, consequently, t is real and symmetric. Thus it may be diagonalized by a unitary matrix U . This matrix relates the physical diffractive states $|i\rangle$ to the diffractive scattering eigenstates $|\psi_k\rangle$ which, by definition, do not undergo inelastic diffractive transitions

$$|i\rangle = \sum_{k=1}^N U_{ik} |\psi_k\rangle \quad (3)$$

$$\langle \psi_k | t | \psi_k \rangle = t_k \delta_{kk} \quad (4)$$

^{*}) Some such effects were already discussed in Ref. 3).

Now the physical amplitudes and cross-sections may be expressed in terms of the real and positive eigenamplitudes t_k , as it was done to derive the bound (1)²). Before doing so, let us remark that the U matrix elements U_{ik} have a simple interpretation: they are probability amplitudes for the physical state $|i\rangle$ to interact as the k^{th} eigenstate $|\psi_k\rangle$. In particular, the pp elastic amplitude may be written as

$$t_{el} = \langle 1|t|1\rangle = \sum_{k=1}^N |U_{1k}|^2 \langle \psi_k|t|\psi_k\rangle = \sum_{k=1}^N P_k t_k = \langle t \rangle \quad (5)$$

i.e., it is given by the average value of the eigenamplitudes weighted by their couplings to pp state. Since our labelling index k is purely formal, we may now re-label the eigenstates using, as the continuous index, the value of eigenamplitude t_k . Then instead of the probability distribution P_k we will discuss in the following, a continuous probability density function $P(\tau)$ which measures the probability that the pp state interacts like an eigenstate with the amplitude value τ .

It follows from the angular momentum conservation that Eq. (5), as well as Eq. (6) to be derived below, is valid for each impact parameter separately. Thus the eigenamplitude values $t_k(b)$ give us the opacities of eigenstates as functions of impact parameter.

Now let us express the inelastic diffractive cross-section in terms of the eigenamplitude spectrum. We have

$$\begin{aligned} \sigma_{diff} &= \frac{1}{2} \sum_{i=2}^N |\langle 1|t|i\rangle|^2 = \frac{1}{2} [(\langle 1|t^2|1\rangle) - (\langle 1|t|1\rangle)^2] = \\ &= \frac{1}{2} \left[\sum_{k=1}^N |U_{1k}|^2 t_k^2 - \left(\sum_{k=1}^N |U_{1k}|^2 t_k \right)^2 \right] \end{aligned} \quad (6)$$

and using the probability interpretation, we can write it as

$$\sigma_{diff}(b) = \frac{1}{2} (\langle t^2 \rangle - \langle t \rangle^2) = \frac{1}{2} D_t^2(b) \quad (7)$$

This relation between the inelastic diffractive cross-section and the dispersion of the eigenamplitude spectrum expresses, in clear and compact form, the ideas of Good and Walker⁹⁾ according to which the inelastic diffraction is a regeneration process generated by the different absorption of various eigenstates. We are now able to use this idea to investigate the shape of the eigenamplitude spectrum.

To perform a quantitative analysis, we have to assume [again following Refs. 2) and 4)] that all the diffractive transitions are of the absorptive type, as seems to be the case for high-energy elastic scattering. Consequently, the eigenamplitudes are bounded by

$$0 \leq t_k(b) \leq 1 \quad (8)$$

From experiment we know the elastic profile at ISR energy¹⁰⁾, i.e., the average of eigenamplitude spectrum for each b . We can also estimate the integral of $D_t^2(b)$, that is, the total inelastic diffractive cross-section. The data for the ratio $\sigma_{\text{diff}}/\sigma_{\text{el}}$ are shown in Fig. 1. Although they are not too exact and sometimes even mutually inconsistent [due partially to the different definitions of diffraction in different papers of Ref. 11)], we can conclude rather safely that the inelastic diffractive cross-section is not too different from the elastic one, i.e., somewhere between 6 and 9 mb in the Fermilab-ISR energy range. Now, given $\langle t \rangle$ for each b , we have calculated the dispersion and resulting inelastic diffractive cross-section for different parametrizations of $P(t)$ around $\langle t \rangle$. Some of the results are shown in Fig. 2. The "reasonable" spectra peaking around its mean value (the "triangular" and "rectangular" examples) are shown to produce σ_{diff} below 2 mb. Even the spectrum covering smoothly all the allowed t range (linear case) results in much too small σ_{diff} . We can summarize our findings as follows.

The experimental size of σ_{diff} implies that, at least for the impact parameters contributing most of σ_{diff} ($b = 0.5 - 1.0$ fm), the eigenamplitude spectrum is double-peaked (as in the last example of Fig. 2). The pp physical state consists mainly of nearly black ($t_k \cong 1$) or nearly transparent ($t_k \cong 0$) eigenstates. This result contradicts dramatically the idea suggested by many authors^{9), 12)} that the physical pp state is approximately a diffractive eigenstate and, consequently, perturbative methods may be successfully applied for the study of diffraction. On the other hand, we disagree also with the quark-model-based guesses²⁾ that all the eigenchannels will be approximately equally absorbed. Hadrons are

semi-transparent, not because the relevant eigenstates are semi-transparent, but because both black and transparent eigenstates contribute significantly to the typical interactions.

Note that the eigenamplitude spectrum is closer to the extreme shape producing maximal diffraction (two δ peaks at $t=0$ and $t=1$) than to the "reasonable" single-peaked distributions. Our results clearly show that the diffraction is nearly as large as allowed by unitarity.

The surprising observation of double-peaked eigenamplitude spectrum induced us to speculate about its possible origin. Let us note here two related remarks. First, if one expresses the eigenamplitudes t_k in terms of "eigeneikonals" Ω_k

$$t_k = 1 - \exp(-\Omega_k) \quad (9)$$

the double-peaked eigenamplitude spectrum may be described by a smooth and monotonical spectrum of eigeneikonals with a rather long "tail" at high Ω_k values. Thus the transition between the "transparent" and "black" contributing eigenstates may be quite smooth when analyzed in terms of eikonals.

Secondly, let us recall the Good-Walker interpretation of eigenstates as the states with definite numbers of "bare" particles ¹⁰⁾. If we think of proton-proton collision in terms of a parton model ¹³⁾, it is tempting to identify the "transparent" eigenstates with "bare valence quarks" states and the "black" component with states having "sea-quarks" and/or gluons present [in some models ¹⁴⁾ gluons are supposed to be responsible for non-diffractive production]. Obviously, it is not clear why the number of "bare" particles cannot change in diffractive transitions, and such a model would require much more work to become quantitative.

Independently of the above speculations, we believe that in any model our information about the spectrum of eigenamplitudes is an important clue and suggests very rich internal structure of the proton.

3. MULTICHANNEL EIKONAL ANALYSIS

The common origin of elastic and inelastic diffraction suggests the plausibility of generalization of the usual eikonal formula

$$t_{el} \equiv t_{11} = 1 - \exp(-\Omega_{11}) \quad (10)$$

into the matrix formula

$$t = 1 - \exp(-\Omega) \quad (11)$$

where both t and Ω are diffractive $N \times N$ matrices. Comparing the second-order expansion of elastic amplitude given by matrix formula (11) with the standard eikonal result, we find

$$t_{11}(b) = \Omega_{11}(b) - \frac{1}{2!} \sum_{k=1}^N [\Omega_{1k}(b)]^2 \quad (12)$$

instead of

$$t_{11}(b) = \Omega_{11}(b) - \frac{1}{2!} [\Omega_{11}(b)]^2 \quad (13)$$

i.e., absorptive corrections are now increased by the contribution of inelastic diffraction, as in the Blankenbecler scheme ¹⁾. Thus obviously the eikonal needed to fit the data by formula (12) has to differ significantly from that of formula (13), at least for small b where matrix elements are non-negligible compared to 1. This effect should be even more pronounced in the full exponential formulae (10) and (11). For large b the square terms may be neglected and the eikonal should approach, in both cases, the measurable amplitude.

In the standard approach, the Chou-Yang prescription of calculating the eikonal from a form factor convolution ⁷⁾ was quite successful ⁸⁾. We can ask now if this will change in our approach. We have found that the difference will be indeed very significant.

To show this, let us consider the simple case in which $N=2$, i.e., all the inelastic channels are included in one off-diagonal element. Moreover, we assume the same b dependence of all the eikonal matrix elements ^{*)}

$$\Omega_{ik}(b) = c_{ik} \Omega(b) \quad (14)$$

Knowing the shape of $t_{11}(b)$ and the total inelastic diffractive cross-section which is $t_{12}(b)$ squared and integrated over b^2 , we can try to

*) This is not incompatible with inelastic diffraction being more peripheral than elastic scattering. As noted already ¹⁵⁾, off-diagonal eikonals are in this parametrization more strongly absorbed for small b .

find $\Omega(b)$ compatible with this input. We have found that the upper limit of σ_{diff} in this parametrization is compatible with the experimental lower limit, i.e., about 6 mb. Thus, the shape of the eikonal could be estimated, in principle, by maximizing the resulting σ_{diff} . (In fact, one of the parameters then goes to infinity, and to keep an analytic formula we have fixed it at a finite value producing σ_{diff} about 5% below maximum.) The result of the fit is shown in Fig. 3, together with the standard Chou-Yang shape resulting from dipole form factors. We see a huge effect -- including the inelastic diffraction -- enhances the values of the elastic eikonal at small b by two orders of magnitude. Unfortunately, the detailed shape of the enhancement is strongly dependent on the parametrization chosen. Introducing, in the inelastic eikonal, the terms vanishing at $b=0$ (as suggested by the non-conservation of s channel helicity), one can even produce a non-central elastic eikonal. In all cases, however, the enhancement of the elastic eikonal expected from the comparison of formulae (10) and (11) is a large and clearly visible effect. We regard our result as a significant suggestion that the matter distribution in a proton may well be very different from the charge distribution as measured by form factors. The apparent ("gluonic") neutral "core" seems to dominate the strong interactions.

As a by-product of formula (11), we may note that indefinitely increasing eikonals do not lead inevitably to the saturation of the black disc limit for the elastic amplitude. According to (5) and (9), we can write

$$t_{11} = 1 - \sum_{k=1}^N P_k \exp(-\Omega_k) \quad (15)$$

The sum does not vanish if at least some of the eigeneikonals Ω_k remain finite, which may happen even if all the eikonals Ω_{ik} increase indefinitely. Thus hadrons may be asymptotically semi-transparent, although they interact as strongly as possible. This should be kept in mind in the following discussion of the asymptotic behaviour.

4. AN "EFFECTIVE UNITARITY BOUND" AND ASYMPTOTIC BEHAVIOUR

The impact parameter representation was found recently to be quite useful in formulating the asymptotic predictions concerning the energy dependence of elastic amplitude. Whereas in the standard Chou-Yang picture ⁷⁾ the eikonal formula suggested the energy independent profiles at high energy, Cheng and Wu ¹⁶⁾, using field theory analogies, predicted the asymptotic saturation of the black disc limit with increasing disc radius. This

corresponds to the power-like increase of the eikonal in standard formula (10). Consequently, since the ratio σ_{el}/σ_{tot} then has to approach 1/2, no place is left in the Pumplin bound (1) for inelastic diffraction, and one predicts

$$\sigma_{diff}/\sigma_{el} \xrightarrow{s \rightarrow \infty} 0 \quad (16)$$

As we have seen from Fig. 3, data from the available energy range do not support this prediction. In fact, some fits ¹⁷⁾ even suggest a rise of the ratio (16) throughout the NAL and ISR energy range, where other "asymptotic" effects of the Cheng-Wu model seem to be clearly visible. This casts some doubts on the validity of this asymptotic prediction. Now, in the preceding section we have seen that a substantial inelastic diffractive contribution changes the eikonal picture significantly. Thus we can ask for a plausible asymptotic limit compatible with a non-vanishing ratio (16). From the Pumplin bound we learn immediately that the effective unitarity bound for the elastic profile is then below 1 (e.g., if the approximate asymptotic equality between elastic and inelastic diffraction holds locally in b , the bound is about 1/2). If inelastic diffraction is non-negligible, hadrons cannot become black -- they are semi-transparent, even at asymptotic energies. According to the preceding remarks, this does not contradict the indefinite increase of the eikonal, as expected from field theory analogies.

The actual asymptotic shape of elastic profile depends obviously on the assumptions adopted. The local equality of elastic and inelastic diffraction as suggested above, would lead to a plateau at a level of about 1/2 (perhaps preceded by a peak at small b where inelastic diffraction is discriminated against by the vanishing of helicity non-conserving terms). This is not incompatible with recent data analyses ¹¹⁾ which show that the increase of σ_{tot} in the ISR range comes almost entirely from the large b region, where the amplitude is rather small (see Fig. 4), and that there is no indication for a rise at small b ¹⁸⁾. Independent of the details, non-negligible inelastic diffraction provides a simple qualitative explanation for the observed (approximate) geometrical scaling ⁹⁾. Since for small b the effective unitarity limit is nearly saturated, the relative rise becomes stronger with increasing b (decreasing amplitude). For a profile which is approximately Gaussian, such an energy dependence may be always rather well approximated simply by increasing the width of distribution.

5. CONCLUSIONS

We have investigated the absorption effects originating from the existence of inelastic diffraction. We have shown that the experimental evidence for comparative strength of elastic and inelastic diffraction suggests very large variations of opacity for the diffractive scattering eigenstates to which the physical hadrons couple. The large size of inelastic diffraction implies that the effects discussed here are very important, and any analysis of elastic scattering neglecting them cannot be reliable. In particular, we have discussed the Chou-Yang eikonal model and have shown the necessity of significant modifications in this standard approach. Our results suggest the existence of a "neutral core" in the proton, which is even more important in hadronic interactions than the proton's charged constituents. We have discussed also the energy dependence of the impact parameter profiles and indicated the plausibility of a "grey disc limit" in which hadrons are asymptotically semi-transparent with average opacity significantly below one.

To summarize, we have demonstrated explicitly the importance of inelastic diffraction in understanding absorptive effects in elastic scattering. We hope that in the near future more quantitative investigation along this line will be possible which will restrict the ambiguities still present in our approach and will improve significantly our knowledge of hadronic interactions.

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FIGURE CAPTIONS

- Fig. 1 : A compilation of $\sigma_{\text{diff}}/\sigma_{\text{el}}$ estimates for pp scattering. Crosses, circles, dots, open and black squares, down- and up-edged triangles represent the data of Refs. 11). The curve results from the fit of Ref. 17).
- Fig. 2 : Various possible probability distributions describing the decomposition of pp state into diffractive eigenstates for three values of b . Resulting integrated diffractive cross-section σ_{diff} is presented in the last column for each distribution.
- Fig. 3 : Dashed line is an example of eikonal calculated assumed two-channel approximation and a common b dependence of all the eikonal matrix elements. Corresponding σ_{diff} is about 6 mb. Chou-Yang fit calculated from the dipole form factor ⁷⁾ is shown as a solid line.
- Fig. 4 : Suggested asymptotic limit (shaded line) as compared with the black disc limit and energy dependence of experimental shape of elastic profile ¹⁰⁾.

FIG. 1

SPECTRUM	$b \approx 0$ $\langle t \rangle = 0.75$	$b \approx 0.6 f$ $\langle t \rangle = 0.5$	$b \approx 1.0 f$ $\langle t \rangle = 0.25$	σ_{diff} [mb]
TRIANGLE				~ 1.0
RECTANGLE				~ 1.9
LINEAR				~ 2.3
DOUBLE LINEAR				~ 6.3

FIG. 2

FIG. 3

FIG.4