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ON THE NATURE OF ABSORPTION *)

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A B S T R A C T

The imaginary helicity non-flip ω exchange amplitudes in KN and NN scattering are determined versus t and s from data on elastic differential cross-section differences. The ω universality prediction

$$\text{Im } \omega_N(t) = 3 \text{Im } \omega_K(t)$$

is found to be satisfied for $0 \leq |t| \leq 0.5$, indicating that the absorptive cuts at small t preserve universality. The impact parameter distributions of the ω amplitudes show :

- i) a peripheral peak centered around $b \simeq 1$ fermi, with $\Delta b \simeq \pm 0.5$ F in KN and $\Delta b \simeq \pm 0.75$ F in NN;
- ii) a sizeable negative contribution at small b , more negative in NN than in KN,
- iii) a smaller tail of negative contributions around $b \simeq 2$ F.

Strong absorption of the ω pole imaginary amplitude with λ values around two is needed to reproduce this structure. A new version of the absorption model, suggested by π N amplitude analysis, is confirmed by our results.

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1. INTRODUCTION

Experimental studies of two-body high energy scattering have led to a fairly detailed outline of the systematics of separated amplitudes. Sufficient experimental information on polarization and spin correlation parameters now exists at 6 GeV/c to completely decompose πN scattering amplitudes into isospin and helicity components ¹⁾. High statistics experiments on the difference of particle and antiparticle πN , KN and NN elastic differential cross-sections allow a direct study of $(C=-1)$ ρ and ω amplitudes ²⁾.

The results of various phenomenological studies of the structure of two-body amplitudes can be summarized as follows :

- the simple Regge pole approximation is adequate in helicity flip amplitudes. This is consistent with weak absorption models ³⁾, where Regge cut corrections are suppressed in flip amplitudes.
- the imaginary part of the non-flip amplitude is strongly affected by absorptive corrections and is strongly peripheral, a result suggestive of the strong cut absorption model ⁴⁾.
- although knowledge on the real part of the non-flip amplitude is relatively poor, the real part is less peripheral than the imaginary part and appears to be in qualitative agreement with the Regge pole approximation.

From these empirical systematics we see that the corrections to simple Regge pole exchange can most readily be studied in the imaginary parts of the helicity non-flip amplitudes. It is the main purpose of this paper to perform such a study for the imaginary parts of the ω non-flip amplitudes $(\text{Im } \omega_K)_{++}$ and $(\text{Im } \omega_N)_{++}$, as determined in KN and NN scattering from differences of particle-antiparticle differential cross-sections.

In Section 2 we compile the experimental information on the structure of the ω exchange amplitudes as a function of t (and of the impact parameter b) and as a function of energy. In Section 3 we present new tests of ω universality for non-zero momentum transfer. Finally, in Section 4, we study the ω exchange amplitudes in the framework of the Gottfried-Jackson absorption prescription and also compare our results to $(\text{Im } \rho_\pi)_{++}$ as obtained from πN amplitude analysis.

2. EMPIRICAL STRUCTURE OF ρ , ω NON-FLIP AMPLITUDES

As pointed out, the imaginary parts of the ρ and ω non-flip amplitudes provide an ideal place to study the nature of absorptive corrections to simple Regge pole exchange. These amplitudes can be directly determined from data on πN , KN , NN differential cross-sections. As an example, consider the case of KN scattering, where

$$A(K^{\mp}p) = P + P' \pm \omega + A_2 \pm \rho \quad (1)$$

Using the experimentally verified facts that

- i) the $K^{\mp}p$ forward differential cross-sections are dominated by the helicity non-flip amplitude;
- ii) the P, P', ω couple mainly to the helicity non-flip amplitude;
- iii) the ρ, A_2 contribute mainly to helicity flip amplitudes and even these flip contributions are relatively small;

equation (1) can be written as

$$\frac{d\sigma}{dt}(K^{\mp}p) = |P + P' \pm \omega|^2 \quad (2)$$

or

$$\frac{d\sigma}{dt}(K^{\mp}p) \approx |P + P'|^2 + |\omega|^2 \pm 2 \operatorname{Im}(P + P') \operatorname{Im} \omega \quad (3)$$

Here we have made the justifiable approximation that the $P + P'$ contribution is mainly imaginary at small t . One can verify from $K_L p \rightarrow K_S p$ data that the $|\omega|^2$ contribution to the right-hand side of (3) can reasonably be neglected even down to energies as low as 2 GeV/c⁵). Therefore, we can calculate $\operatorname{Im} \omega$ directly from elastic scattering data as follows :

$$\Delta_K \equiv \frac{\frac{d\sigma}{dt}(K^-p) - \frac{d\sigma}{dt}(K^+p)}{\sqrt{8 \left[\frac{d\sigma}{dt}(K^-p) + \frac{d\sigma}{dt}(K^+p) \right]}} = \operatorname{Im} \omega_K \quad (4)$$

If all the assumptions going into the derivation of (4) are valid for NN scattering, we obtain in analogy to (4)

$$\Delta_N \equiv \frac{\frac{d\sigma}{dt}(\bar{p}p) - \frac{d\sigma}{dt}(pp)}{\sqrt{8\left[\frac{d\sigma}{dt}(\bar{p}p) + \frac{d\sigma}{dt}(pp)\right]}} = \text{Im } \omega_N \quad (5)$$

Using the existing data ⁶⁾ on KN and NN differential cross-sections we are able to determine $\text{Im } \omega_K$ at four different energies ranging from 2 to 7 GeV/c (Fig. 1) and $\text{Im } \omega_N$ at six different energies ranging from 3 to 16 GeV/c (Fig. 2) ^{*}). In Figs. 1 and 2 we show smooth interpolations of the data on Δ_K and Δ_N . These interpolations were subsequently used in partial wave analysis using the transformation

$$\text{Im } \omega_{K,N}(b) = \frac{1}{\sqrt{\pi}} \int \text{Im } \omega_{K,N}(t) J_0(b\sqrt{-t}) \sqrt{-t} d(\sqrt{-t}) \quad (6)$$

Our results for $\text{Im } \omega_{K,N}$ as a function of impact parameter are displayed in Figs. 3 and 4.

Although the experimental determinations of $\Delta_{K,N}$ are sensitive to the over-all normalization and detailed t dependence of the different experiments, it is encouraging to see how we get similar results from evaluations of $\text{Im } \omega_{K,N}$ independently at different energies. In the Regge pole model we expect

$$\text{Im } \omega_{K,N} \sim s^{n-1} \quad (7)$$

with

$$n \approx \frac{1}{2} + t \quad (8)$$

The energy dependence we find for $\text{Im } \omega_{K,N}$ is consistent with Eqs. (7) and (8).

A similar determination of $\text{Im } f$ from $d\sigma/dt(\pi^\mp p)$ data is more difficult due to the near equality of $d\sigma/dt(\pi^- p)$ and $d\sigma/dt(\pi^+ p)$, but nevertheless, can still be performed. We refer to Refs. 1) and 5) for a complete discussion concerning the determination of the imaginary part of the f non-flip amplitude.

^{*}) Although not crucial in these calculations, the $t=0$ values include corrections to the optical point due to the ratio of real to imaginary parts, as found from data or empirical interpolations of data.

3. NEW TESTS OF ω UNIVERSALITY

One of the most intriguing results of the total cross-section data in the 30 - 70 GeV/c energy range was the continued success of the ω universality prediction ⁷⁾

$$\text{Im } \omega_N(t=0) = 3 \text{ Im } \omega_K(t=0) \quad (9.a)$$

or

$$\sigma_t(\bar{p}p) - \sigma_t(pp) \approx 3 [\sigma_t(K^-p) - \sigma_t(K^+p)] \quad (9.b)$$

This relation also correctly correlates the total cross-section data over the 3 - 20 GeV range ⁸⁾.

We briefly recall the theoretical assumptions required in the derivation of Eq. (9). A "road map" to the theory is given in Fig. 5. The t channel helicity non-flip amplitude ^{*}) for Regge pole vector meson exchange has the structure ^{8),9)}

$$\beta_V(t, \alpha) \sim \left\{ -h [1 - t/4M^2] + \alpha(t) [g + h] \right\} \quad (10)$$

where g and h are the charge and anomalous moment couplings to baryons, respectively

$$g \gamma_\mu - h \frac{\gamma_\nu}{2M} \sigma_{\mu\nu}$$

At $[t=0, \alpha(t)=1]$ we know from the experimental magnetic moments that for the $I_t=0$ part of the photon the tensor coupling h is less than 10% of the vector coupling g . Using vector meson dominance of the electromagnetic current we can conclude that the ω couples mainly to nucleons through the vector coupling g with ⁹⁾

$$h_\omega/g_\omega \approx -0.1 \quad \text{at } [t=0, \alpha(t)=1] \quad (11)$$

*) In the s and t range relevant to our analysis, results for the t channel non-flip amplitude are also true for the s channel non-flip amplitude. Equation (10) is based on the sense mechanism for the vector meson exchange amplitude. For the nonsense mechanism the first term of β_V also has a factor of $\alpha(t)$. Our results regarding the ω amplitude are independent of the choice of mechanism, inasmuch as $h_\omega \approx 0$.

The assumption of ω universality (see Fig. 5) is that this is still the case at $[t=0, \alpha(t) \approx \frac{1}{2}]$, leading to essentially pure F coupling of the ω Regge exchange to nucleons and to relation (9).

From the experimental data on (4) and (5) we can now test ω universality as a function of momentum transfer t . The results are given in Fig. 6. The relation

$$\text{Im } \omega_N(t) = 3 \text{ Im } \omega_K(t) \quad (12)$$

is satisfied out to $t \simeq -0.5$ as shown in Fig. 6 at $p_{\text{LAB}} = 3$ and 5 GeV/c. Although the error bars are larger, the ω universality relation is also satisfied at higher energies out to $t \simeq -0.5$. At larger values of $|t|$ the ω universality relation (12) breaks down because of the different structure⁵⁾ of the left and right-hand sides of Eq. (12) beyond $|t| \simeq 0.5$, as can be seen in Figs. 1 and 2. In Fig. 7 we show a test of ω universality out to larger t using a recent Argonne experiment at 3.65 GeV/c¹⁰⁾.

The fact that Eq. (12) is satisfied for small non-zero t is in fact a non-trivial extension of ω universality applied to total cross-sections. This can be seen as follows: ω universality assumes g and h to be slowly varying functions of t and the fact that $h_\omega \approx 0$ at the photon pole leads to a pure F coupling of ω exchange and to Eq. (12). However, under the same assumptions, we obtain the Regge pole limit

$$\text{Im } \omega_{K,N} \sim \alpha(t) g \quad (13)$$

with g a slowly varying function of t . This result can be normalized at $t=0$. The prediction, assuming that g is constant, is shown by the dashed lines in Fig. 6 and does not agree with the data. It is not surprising that the simple Regge pole prediction (13) breaks down since we expect the imaginary part of non-flip amplitudes to be strongly affected by cuts. The total Regge exchange amplitude (i.e., poles + cuts) empirically satisfies ω universality. The data in Fig. 6 nicely exhibit the sign of the cut correction to Regge poles; ω universality unambiguously predicts negative sign or destructive cut corrections at small t . The deviation from the pole prediction gives the structure of absorptive corrections in momentum transfer t .

In current absorption models the cut is calculated as a convolution integral of the bare ω Regge pole $R(t)$ with the $I_t=0$ elastic $P+P'$ T matrix

$$R \otimes T_{P+P'}$$

The convolution is strongly weighted towards small $|t|$ values. The requirement of ω universality gives $R(t) \propto \gamma_\mu$, which at high s and small $|t|$ is approximately equivalent to s channel helicity conservation. Therefore, from s channel helicity conservation for the $I_t=0$ amplitude $T_{P+P'}$, it follows that the absorptive corrections generated from the convolution of $R(t)$ and $T_{P+P'}$ preserve $T \propto \gamma_\mu$. The fact that the isoscalar "charge" distribution ratio $\omega_K(t)/\omega_N(t) = 1/3$ is likewise preserved by the absorptive cuts is quite remarkable.

In complete analogy to the ω , one can consider ρ universality. At the photon pole $[t=0, \alpha(0)=1]$ the isovector part of the electromagnetic current has an appreciable tensor coupling^{8),9)} and so pure F coupling is not expected. In contrast, the quark model^{8),11)} yields the relation

$$\text{Im } \omega_K(t) = \frac{3}{2} \text{Im } \rho_\pi(t) \quad (14)$$

which is equivalent to pure F coupling to nucleons for both ω and ρ . Here ω_K is as before defined by Eq. (4)^{*}) and ρ_π stands for the non-flip ρ exchange amplitude in πN scattering. The latter can be obtained from πN amplitude analysis at 6 GeV/c¹⁾ and can be compared through relation (14) to ω_K obtained around 5.0 GeV/c from $K^{\mp}_p$ differential cross-sections. The result is shown in Fig. 8. The slopes of the ρ and ω amplitudes turn out to be quite different, indicating that (14) fails as a function of t giving further confirmation of the failure of the quark model found in total cross-section fits⁸⁾.

In summary we have found that the full Regge amplitude (pole + cuts) obeys the ω universality relation for $0 \leq |t| \leq 0.5$. Assuming that the Regge pole amplitude yields F type coupling at $t=0$, the absorptive cuts must preserve the universal strength of this coupling.

*) Strictly speaking $\text{Im } \omega_K(t)$ in Eq. (4) includes both ω and ρ non-flip contributions to K_p elastic scattering, but empirically the ρ_K/ω_K amplitude ratio from σ_t fits is $\approx 1/6$ and the ρ_K contribution can consequently be neglected relative to ω_K .

4. PARTIAL WAVE STRUCTURE OF ABSORPTION

Figures 3 and 4 show a rather accurate determination of the partial wave or impact parameter structure of the ω amplitude. Consistent shapes of partial wave distributions are found in independent determinations at different energies, using the results of different experimental groups. The general qualitative features of the impact parameter distributions are :

- a peripheral peak centered around $b \simeq 1$ fermi;
- a sizeable negative contribution (i.e., opposite sign to the peripheral partial waves) at small impact parameters;
- a smaller tail of negative contributions around $b \simeq 2$ fermi.

In the following we shall investigate these features in the context of the absorption model. In an absorption model the partial wave amplitudes are calculated using the Sopkovich prescription ¹²⁾

$$A_J = R_J S_J^{el} \quad (15)$$

where S_J^{el} and R_J are the partial wave amplitudes of the elastic S matrix and bare (Regge) exchange amplitude, respectively. Thus we have in the impact parameter representation $[b = (J + \frac{1}{2})/q]$

$$A(b) = R(b) S^{el}(b) \quad (16)$$

As the elastic scattering is largely imaginary, (16) can be written as

$$A(b) = R(b) - |T^{el}(b)| R(b) \quad (17)$$

where

$$S^{el}(b) = 1 + i T^{el}(b) \quad (18)$$

The double scattering term in (17) can receive additional contributions from other than elastic intermediate states ⁴⁾ such that effectively

$$A(b) = R(b) - |T^{eff}(b)| R(b) \quad (19)$$

where T^{eff} is usually parametrized as a constant factor λ times T^{el}

$$T^{eff}(b) = \lambda T^{el}(b) \quad (20)$$

In Section 2 we have shown how, in the case of the ω exchange, $A(b)$ can be obtained from data on KN and NN scattering. We now consider a typical $\text{Im } \omega(b)$ distribution, e.g., KN scattering at $p_{\text{LAB}} = 5 \text{ GeV/c}$. $T^{\text{el}}(b)$ can be obtained at the same energy using elastic KN differential cross-sections. We partial wave analyze K^+p scattering, in analogy to (6)

$$|T^{\text{el}}(b)| = \frac{1}{\sqrt{\pi}} \int \left[\frac{d\sigma}{dt}(K^+p) \right]^{\frac{1}{2}} J_0(b\sqrt{-t}) \sqrt{-t} d(\sqrt{-t}) \quad (21)$$

The results are given in Fig. 9. Having calculated $T^{\text{el}}(b)$ from data, any ansatz for the bare Regge exchange $R(b)$ will lead through Eqs. (19) and (20) to a prediction for the shape of $A(b)$ [$\text{Im } \omega_K(b)$ in our example] that can be compared to the partial wave distribution directly obtained from data. Below we will discuss this comparison in detail for two classes of models giving a definite prescription for the bare Regge exchange : dual models ¹³⁾ and strong cut models.

The Veneziano model gives

$$R(t) = a \Gamma(1-\alpha(t)) (1 - e^{-i\pi\alpha(t)}) \left(\frac{s}{s_0} \right)^{\alpha(t)-1} \quad (22)$$

with

$$s_0 = 1/\alpha' \quad (23)$$

In Fig. 10 we compare the absorbed exchange to the data for a series of λ values. The normalization parameter a [see Eq. (22)] was adjusted to reproduce the over-all partial wave distribution as well as possible. Needless to say, the Argonne version ³⁾ of the absorption model ($\lambda=1$) fails dramatically in the low partial waves. The high partial waves from an absorbed dual model are too small, whatever the value of λ .

The essential prediction of the dual model in this context is the scale of the Regge exchange [cf., Eq. (23)]. Relaxing this constraint, we obtain a simple Regge pole with wrong signature nonsense zeros (WSNZ)

$$R(t) = a \Gamma(1-\alpha(t)) (1 - e^{-i\pi\alpha(t)}) e^{ct} s^{\alpha(t)-1} \quad (24)$$

Here we have absorbed the scale factor s_0 into the exponent c . In Fig. 11 we show how well such a model can reproduce the trends of the data. The scale factor (typically $s_0 \simeq 0.1$) is far removed from the Veneziano prediction.

In strong cut models the bare Regge pole input is structureless ⁴⁾, i.e., a Gaussian in impact parameter space or a simple exponential in the t dependence of the residue

$$R(t) = a e^{-i \frac{\pi}{2} \alpha(t)} e^{ct} s^{\alpha(t)-1} \quad (25)$$

Absorbed calculations with this Regge pole input are compared to the data for a series of λ values in Fig. 12.

We believe that this method of studying absorptive corrections and the structure of Regge pole exchanges is much more illuminating than direct fits to scattering data. We find strong absorptive corrections to be required in helicity non-flip amplitudes and the structure of duality inspired Regge poles ($s_0 \approx 1/\alpha'$) to be inconsistent with the data. Even the partial wave distributions, generated through the absorption model from (24) or (25) are not satisfactory. We observe a mismatch of low and high partial wave components (see Figs. 11 and 12). This confirms similar findings in the case of ρ exchange in πN scattering ^{14),15)} and absorbed π exchange in np charge exchange reactions ¹⁶⁾.

The failure of the type of absorption models defined by Eqs. (19) and (20) can be exhibited directly from data by calculating the Regge pole input required to fit the $\text{Im } \omega_K(b)$ data at 5 GeV/c. Solving (19) for $R(b)$ we obtain

$$\text{Im } R(b) = \frac{\text{Im } A(b)}{1 - \lambda |T^{el}(b)|} \quad (26)$$

with

$$\text{Im } R(t) = \sqrt{\pi} \int \text{Im } R(b) J_0(b\sqrt{-t}) b db \quad (27)$$

The result for $\text{Im } R(t)$ is shown in Fig. 13b. The absorption model requires a Regge pole input with zeros at $t \simeq -0.3$ and $t \simeq -1$. The example of Fig. 13b is calculated with $\lambda = 2$, but the position of the first zero is required to be between $t \simeq -0.1$ and $t \simeq -0.3$ whatever the value of λ . In a Regge pole model with WSNZ we expect $\text{Im } R(t)$ to have a single zero at $t \simeq -0.5$; in a strong cut model $\text{Im } R(t)$ is structureless. Our simple calculation shows that absorptive corrections calculated through Eqs. (19) and (20) are inadequate to reconcile the Regge pole approximation with the data.

The failure of conventional absorption model calculations to reproduce the empirical real part of the ρ non-flip amplitude in πN scattering¹⁾ and to account for the breaking of exchange degeneracy in line reversal reactions¹⁷⁾ may well be associated with the approximation¹⁸⁾

$$T^{\text{eff}} \approx i\lambda |T^{\text{el}}| \quad (28)$$

which leads to completely destructive cuts. A substantial real part of T^{eff} was found by Johnson¹⁹⁾ in calculations of the empirical T^{eff} needed to reproduce $\pi^- p \rightarrow \pi^0 n$ separated amplitudes from a ρ Regge pole input. If we assume that Johnson's form for T^{eff} (shown in Fig. 13c) can be taken over to πN scattering^{*)}, we can again calculate $\text{Im} R(t)$ for ω exchange directly from data on $\text{Im} A(t)$. In this calculation we need to use the relation

$$\text{Re} R(t) = \tan \frac{\pi\alpha}{2} \text{Im} R(t)$$

for the unabsorbed ω Regge pole amplitude. The results are given in Fig. 13d^{*)}. For $\text{Im} R(t)$ we obtain a standard ω Regge pole amplitude with a WSNZ at $t \approx -0.5$. The inclusion of a real part for T^{eff} in absorption model calculations clearly deserves further attention.

We end with a comparison of the structure of $\text{Im} \rho_\pi$, $\text{Im} \omega_K$, and $\text{Im} \omega_N$ from Refs. 14), 15) and Figs. 3 and 4. The impact parameter distributions of these vector meson exchange amplitudes all exhibit a peripheral peak centered about $b \approx 1$ fermi. The width of the peak in NN scattering, $\Delta b \approx \pm 0.75$ F is greater than in KN or πN , where $\Delta b \approx \pm 0.5$ F. The sharper edge of the peripheral ω in KN than in NN is related to the oscillations about zero of $\text{Im} \omega_K(t)$ which do not occur in $\text{Im} \omega_N(t)$ (see Figs. 1 and 2). The size of the negative low partial wave contribution is smaller for ρ exchange^{14),15)} than for ω exchange, suggesting a possible correlation of this low partial wave effect with annihilation where $I=0$ dominates $I=1$ amplitudes²⁰⁾.

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*) We used $\lambda = 2$ as a boost factor in taking the T^{eff} from πN scattering over to KN scattering. Although results are shown only at 5 GeV/c, similar conclusions were obtained at the other energies.

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FIGURE CAPTIONS

- Figure 1 : Imaginary helicity non-flip ω exchange amplitude $[\text{Im } \omega_K(t)]$ in KN scattering.
- Figure 2 : Imaginary helicity non-flip ω exchange amplitude $[\text{Im } \omega_N(t)]$ in NN scattering.
- Figure 3 : Impact parameter distribution of $\text{Im } \omega_K$.
- Figure 4 : Impact parameter distribution of $\text{Im } \omega_N$.
- Figure 5 : Sketch showing momentum transfer regions where vector meson dominance, universality, and Regge theories apply.
- Figure 6 : Test of ω universality in the t range $0 \leq |t| \leq 0.5 \text{ (GeV/c)}^2$. The dashed line is the Regge pole prediction with constant residue appropriately normalized at $t=0$.
- Figure 7 : Test of ω universality out to large momentum transfers.
- Figure 8 : Test of quark model relation $\text{Im } \omega_K(t) = \frac{3}{2} \text{Im } \rho_\pi(t)$. This prediction also follows from universal couplings for both ω and ρ exchanges.
- Figure 9 : Impact parameter distribution of K^+p elastic scattering at 5 GeV/c.
- Figure 10 : Comparison of absorbed ω Regge pole from the Veneziano model (i.e., $s_0 = 1/\alpha'$) with the KN data at 5 GeV/c of Fig. 3.
- Figure 11 : Comparison of absorbed simple Regge pole with the data on the ω amplitude at 5 GeV/c in Fig. 3.
- Figure 12 : Results of absorption on a structureless Regge pole input, computed with the data on the ω exchange amplitude at 5 GeV/c from Fig. 3.

$$\left\{ \frac{d\sigma}{dt} (K^-p) - \frac{d\sigma}{dt} (K^+p) \right\} / \left\{ 8 \left[\frac{d\sigma}{dt} (K^-p) + \frac{d\sigma}{dt} (K^+p) \right] \right\}^{\frac{1}{2}}$$

FIG 1

FIG 2

FIG 3

FIG 4

FIG 5

ω UNIVERSALITY

FIG 6

FIG 7

QUARK MODEL RELATION $\text{Im } \omega_K = \frac{3}{2} \text{Im } \rho_\pi$

FIG 8

IMPACT PARAMETER DISTRIBUTION OF K^+p ELASTIC SCATTERING

FIG 9

ABSORBED DUAL MODEL

FIG 10

ABSORBED SIMPLE REGGE POLE WITH WSNZ

FIG 11

ABSORBED STRUCTURLESS REGGE POLE

FIG 12

FIG 13