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A NOVEL INTERPRETATION OF THE HOLE STRUCTURE IN $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$ *)

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A B S T R A C T

A natural interpretation of the hole structure exhibited by the recent data for $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$ in flight, and not explained by the Veneziano model, is proposed. A dual formula with properties analogous to those of Veneziano, Virasoro and Mandelstam, but with a different dynamical content, is presented.

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The data for $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$ at rest ¹⁾ have raised considerable interest for the presence of a deep hole at the centre of the Dalitz plot. Lovelace ²⁾ suggested an elegant interpretation of this hole, as due to one of the zeros produced by the Γ function at the denominator of the Veneziano formula ³⁾

$$\frac{\Gamma(1-\alpha(s))\Gamma(1-\alpha(t))}{\Gamma(2-\alpha(s)-\alpha(t))} \quad (1)$$

where s and t correspond to $m^2(\pi^- \pi^+)$ for the two π^- . Recently, data have appeared for the same process in flight ⁴⁾. Remarkably, at $p_{\text{lab}} = 1.2 \text{ GeV}/c$ [corresponding to $M^2(\bar{p}n) \simeq 4.6 \text{ GeV}^2$] more holes of the kind suggested by the Veneziano formula are observed. But, remarkably too, not all of them are there. While they are present at $(\alpha_s, \alpha_t) = (1.5, 1.5), (2.5, 2.5), (3.5, 1.5), (1.5, 3.5)$, they are absent at $(2.5, 1.5)$ and $(1.5, 2.5)$ (Fig. 1a). These two last holes are missing also at rest ¹⁾, where they should be partly visible.

The Dalitz plot for momenta between 1.3 and $1.6 \text{ GeV}/c$ ⁴⁾ still shows some structure, but it is more uniform and the holes are partly filled. At $p_{\text{lab}} \simeq 1.2 \text{ GeV}/c$ one observes a bump in the cross-section, which comes out particularly clear when the Fermi motion is unfolded ⁴⁾ (Fig. 1b) ^{*}). The threshold, where the holes are also present, is at $M^2(\bar{p}n) = 3.52 \text{ GeV}^2$, i.e., just $1/\alpha' \sim 1 \text{ GeV}^2$ back from the bump. All this seems to suggest that some exchange-degenerate Regge family of resonances dominates in $\bar{p}n$ channel, and that the holes in the Dalitz plot appear in correspondence of the cross-section bumps produced at the integer values of α . We shall return on this point later.

^{*}) To this bump there corresponds some structure also in the energy behaviour of the moments of the rotation functions D_{00}^2 and D_{02}^2 [see Ref. 4].

We are principally interested in the fact that, when the holes are present, they are present only alternately. This is not easy to reproduce with the Veneziano model, also allowing for satellites. In order to fit the data at rest, Altarelli and Rubinstein⁵⁾ (following Lovelace²⁾) give large imaginary parts to the trajectories $\alpha(s)$ and $\alpha(t)$, so that all the zeros in Eq. (1) are sizeably removed from the real axis, and the corresponding holes are filled. The prominent hole at $(\alpha_s, \alpha_t) = (1.5, 1.5)$ is then restored by cancellation of different Veneziano terms. This is somewhat away from the spirit of the original suggestion of Lovelace. For the data in flight, one would require in this way several other terms and cancellations. Bettini et al.⁴⁾ then try to reproduce the new holes in these data assuming dominance of natural parity in the intermediate state. This provides a factor $\epsilon_{\alpha\beta\gamma\delta} p_{\beta}^{(1)} p_{\gamma}^{(2)} p_{\delta}^{(3)}$ before the amplitude $[p^{(1)}, p^{(2)}, p^{(3)}]$ are the momenta of the three pions⁶⁾. Such a factor depresses the Dalitz distribution along the whole boundary of the physical region, and in particular in the strip near $m^2(\pi^-\pi^-) \simeq 0$ where the new holes are present. As the authors admit, this explanation is basically unsatisfactory, since it does not account for the prominent hills present in the corners $m^2(\pi^-\pi^-) \simeq m^2(\pi^+\pi^-) \simeq 0$ (Fig. 1a). A B_5 description does not change the quality of the troubles⁴⁾.

THE PROPOSED STRUCTURE

In the Goebel construction⁷⁾ of the Veneziano formula, one considers two Regge families of resonances (say one in s channel and the other in t channel), takes the "product" of them and then introduces a family of zeros to remove double poles. The Veneziano formula gives a particular prescription for how to take this family of zeros, namely at u fixed. One can look at such a construction also from another point of view. Near the intersection of two resonances the scattering amplitude $A(s, t)$ can be approximated by

$$A(s, t) \simeq \frac{a}{m_a^2 - s} + \frac{b}{m_b^2 - t} \equiv \frac{a(m_b^2 - t) + b(m_a^2 - s)}{(m_a^2 - s)(m_b^2 - t)} \quad (2)$$

The numerator in the last expression is zero along a line in the s, t plane. The orientation of this line depends on the ratio a/b of the resonance residues at the intersection point. When the two Regge families in s and t cross each other, one has then, as a simple consequence of analyticity, a local valley in the neighbourhood of each point where resonances intersect. One may look for patterns in which these local valleys join one to the other in some regular and simple way. The Veneziano formula provides a particular example of such a pattern, corresponding to take all the valleys at u fixed, and consequently $a=b$ at all resonance intersections⁸⁾.

We now propose an alternative pattern, where local valleys are oriented partly at $u=\text{constant}$ (then $a=b$) and partly at $s-t=\text{constant}$ (then $a=-b$). The pattern is represented in Fig. 2b. In the region $s, t \geq 0$, the behaviour of zeros in Fig. 2b gives rise to an alternate presence of holes in the frames formed by the resonances, which is just the feature exhibited by the experimental data (Fig. 1a)⁴⁾. Of course, data give no indications on the behaviour of zeros in the other regions of the Mandelstam plane. Therefore, the part of Fig. 2b concerning the regions outside $s, t \geq 0$ is to be considered as speculative.

The complete structure of Fig. 2b is obtained uniquely from the behaviour of zeros in the $s, t \geq 0$ region if one further assumes that zeros behave everywhere like straight lines. In this case, indeed, each s and t resonance is crossed by an infinite number of $s-t=\text{constant}$ zeros. In order to avoid infinite angular momenta, one is then constrained to introduce a Regge family of u channel resonances, so that all residue zeros but a finite number are removed. The structure comes out in this way uniquely fixed. The u channel resonances so introduced are (in our case) exotic, but non-peripheral (at rest the lowest one would have $J=2$ and $M \simeq 2.2$ GeV). Therefore, they would not be of much harm to the successful predictions of duality.⁹⁾ The whole structure may be expressed in terms

of Γ functions ^{*}). One can verify, with the usual techniques, that within each separate channel the behaviour is similar to that of the Veneziano formula. What is essentially different is only the connection between the various channels. The structure satisfies the so-called supplementary condition ³⁾ $\alpha_s + \alpha_t + \alpha_u = 2$ ^{**)}. This relation, while seems to have some well founded connections with physics (since, for instance, it is approximately satisfied in πp scattering and Λ production), opens on the other hand some problems because of the link it establishes between internal and external masses. In our case it may be written as $\alpha_s(0) + \alpha_t(0) + \alpha_u(0) = -2 - 3 \cdot \alpha' \cdot \mu^2 - \alpha' m^2(\bar{p}n)$. Therefore, when $m^2(\bar{p}n)$ increases $\alpha_u(0)$ should decrease. If the holes in the Dalitz plot are present only in coincidence with cross-section bumps spaced by $1/\alpha' \text{ GeV}^2$, so that the structure is to hold only at the corresponding values of $m^2(\bar{p}n)$, this relation may not be absurd. It could be interpreted as prescribing a progressive decoupling of the exotic resonances with higher spins when $m^2(\bar{p}n)$ increases.

We want to stress again, anyway, that the interpretation we propose for the alternation of holes in the $s, t \geq 0$ region does not imply the existence of exotics and does not have to face the above problems. All these come out if one further assumes straight-line behaviour of zeros outside the experimentally accessible region. Zeros can in general describe other curves, possibly shifting into the

^{*}) Namely, the structure of Fig. 2b corresponds to

$$A(s, t) = \frac{\Gamma(1 - \alpha(s)) \Gamma(1 - \alpha(t)) \Gamma\left(\frac{\alpha(s) + \alpha(t)}{2}\right)}{\Gamma\left(\frac{\alpha(s) - \alpha(t)}{2}\right) \Gamma\left(\frac{\alpha(t) - \alpha(s)}{2} + 1\right) \Gamma\left(\frac{3 - \alpha(s) - \alpha(t)}{2}\right)}$$

with $\alpha(s) = 0.5 + s$. To fix the ideas the $\bar{p}n$ leg has been assumed to have $J = 1$.

^{***)} It has been shown that, assuming wrong signature zeros at high energy, conditions like that are strictly related to the assumption of straight-line behaviour of zeros [Ref. 10), see also Ref. 8)].

complex plane. Apart from the extent with which it is realized in $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$, the structure of Fig. 2b is interesting by itself, since it provides a further example of Regge-behaved crossing-invariant dual structure besides those proposed by Veneziano ³⁾, Virasoro ¹¹⁾ and Mandelstam ¹²⁾. We do not have a proof that it cannot be expressed as a finite superposition of these ones. However, as far as we have been able to see, it should not. As to the phenomenological relevance of the structure, we also notice that its resonance spectrum is just the one expected in a process like Λ production. More detailed considerations on these points will be presented elsewhere.

APPLICATION TO $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$

The behaviour of zeros in the $s, t \geq 0$ region of Fig. 2b reproduces correctly the experimental alternation of holes in the Dalitz plot. This does not imply that an amplitude with such zeros dominates the process. In order to fill the unwanted holes leaving the other ones unchanged, it is sufficient that it gives a 30-40% contribution. The cross-section bump at $M^2(\bar{p}n) = 4.5 \text{ GeV}^2$ is expected to correspond to $\alpha = 4$ or 5. The intermediate angular momenta which probably play a role run therefore from 0 to 5 ^{*)}. It is possible that some angular momenta carry a Veneziano structure, and the other the proposed one.

As to the data at rest ¹⁾, we notice that, because of Bose statistics, an intermediate $J^P = 0^-$ state cannot have a structure like that of Fig. 2b. Our interpretation is therefore not compatible with the current assumption made in the literature that capture from such a state dominates alone $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$ at rest. We think, however, that this assumption can be objected in the light of the resonance bump exhibited by the new cross-section data at $M^2(\bar{p}n) \simeq 4.5 \text{ GeV}^2$ (Fig. 1b). As remarked above, if one goes back by $1/\alpha' \sim 1 \text{ GeV}^2$, one just sits on the threshold $[M^2(\bar{p}n) = 3.52 \text{ GeV}^2]$. The idea of Regge

^{*)} For $\bar{p}p \rightarrow \pi^- \pi^+$ annihilation, in the same momentum range there is evidence for the excitation of waves with $J \leq 5$ [Ref. 13].

recurrence suggests therefore that very near to the threshold there is a resonance, whose α should be 3 or 4 ^{*)}. The presence of such a resonance would make ineffectual the theoretical arguments in favour of S capture dominance. Indeed, for annihilation in deuterium one already expects "a priori" a 3% contribution from P capture (making a cut of 150 MeV/c on the observed momentum of the spectator proton) ¹⁴⁾. It is sufficient therefore that a resonance enhances the amplitude for P capture by a factor $\sim 3-4$ with respect to that of S capture to make the former competitive with the latter. On the experimental side there is nothing at present against this possibility. We therefore conclude that there is no real reason to believe in $J^P = 0^-$ dominance at rest in the considered process, and that very likely the existence of holes in the corresponding Dalitz plot is connected with the presence of a nearby resonance rather than with some peculiarity of the threshold.

*) Exchange degeneracy is also required. If it is the π trajectory that dominates, its coupling to the $\bar{p}n$ vertex should be exchange degenerate with that of A_1 , because of the existence of a forbidden channel in np scattering. The π couples strongly to $\bar{N}N$ and to the 3π channel, as it is known from the analysis of peripheral single pion production. The A_1 has a width of ~ 90 MeV and it decays practically only into 3π . The only known competitor of the π - A_1 exchange degenerate trajectory is the A_2 . The latter, however, seems to couple weakly to $\bar{N}N$, as it is indicated by the energy behaviour of the angular distribution in np charge exchange scattering and $\bar{p}p \rightarrow \bar{n}n$. The widths of its two components A_{2L} and A_{2H} are only ~ 20 MeV. See also Ref. 15).

In conclusion, we have proposed a natural interpretation of the hole structure exhibited by $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$ data, and not satisfactorily explained by the Veneziano model. We have also presented a dual structure, suggested by such an interpretation, which has all the desirable properties of those proposed by Veneziano, Virasoro, and Mandelstam but a different dynamical content.

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FIGURE CAPTIONS

Figure 1 :

Experimental data for $\bar{p}n \rightarrow \pi^- \pi^- \pi^+$ from Ref. 4).

- a) shows the alternate presence of holes in the frames formed by the resonances;
- b) shows the presence of a bump in the cross-section at the momentum where the holes are particularly clear.

Figure 2 :

- a) Representation in the Mandelstam plane of the pattern of zeros and poles of the Veneziano formula. The hole structure predicted for the 3π Dalitz plot is schematically shown (triangle $s, t, u > 0$).
- b) Same as in a) for the novel structure proposed.

FIG.2a

FIG.2b