NEW INTERFERENCE PHENOMENA IN COHERENT PRODUCTION
AND THE GEOMETRY OF DIFFRACTIVE AMPLITUDES

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ABSTRACT

New interference phenomena, recently observed at the ISR in coherent production on deuterons, are analysed in terms of the structure of the elementary nucleon diffractive amplitudes. The sensitive interferometry provided by this two-nucleon system selects a specific form for these amplitudes in terms of helicity-flip components. This analytical form has a direct geometrical interpretation in terms of spatial deformations of the diffracted systems.

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The aim of this letter is to show that new constraints on nucleon diffractive amplitudes arise from a peculiar interference phenomenon, recently observed at the ISR in coherent production on deuterons [1]. We consider, in our analysis, a wide range of analytical forms for the elementary diffractive amplitude on nucleons, with completely different behaviour in impact parameter space. We then show that only a specific class of amplitudes can reproduce satisfactorily the observed interference effect, because of a critical interplay between the positions of the amplitude zeros and the coherence between single and double scattering. For this class of amplitudes a specific geometrical interpretation can be advocated, involving a deformation of the spatial extension of the diffractive states.

The deuteron structure plays a fundamental role in inferring these properties of elementary diffractive amplitudes. It offers in fact, through its well known and very extended spatial structure, an almost ideal interferometer to analyse the details of diffraction-dissociation mechanisms.

The interference effect was observed in two- and three-body coherent diffraction on deuterons at the ISR, in the reactions $nd \rightarrow (p\pi^-)d$ and $pd \rightarrow (p\pi^+\pi^-)d$ at c.m. energies of 37 GeV and 53 GeV, respectively [1]. In both cases the low-mass differential cross-sections display structures at intermediate t -values, as shown, for example, in fig. 1a, where a shoulder appears around 0.3 GeV^2 . This behaviour is consistently present in both reactions and in different mass bins, appearing as a universal feature of coherent diffraction on deuterons.

The interpretation of the data requires the use of Glauber multiple scattering theory, extended to the inelastic case, where the input is given by the elementary diffractive amplitude on free nucleons and the total cross-section of diffractive states. The details of this calculation are given in a more extended paper [1].

We consider here two completely different classes of input amplitudes, already suggested in the literature. The first one [2] is characterized by being *i) purely imaginary, ii) expandable over a set of helicity-flip terms, and iii) intrinsically peripheral in all terms.*

Parametrizing the helicity amplitudes in terms of Bessel functions we get

$$T_{\Delta\lambda}(t) = i C_{\Delta\lambda} e^{at} J_{\Delta\lambda}(R\sqrt{-t}) e^{i\Delta\lambda\phi} \quad (1)$$

$$\frac{d\sigma}{dt} = \sum_{\Delta\lambda} |T_{\Delta\lambda}(t)|^2, \quad (2)$$

where $\Delta\lambda$ is the amount of helicity flip, $J_{\Delta\lambda}$ is the Bessel function of order $\Delta\lambda$, R is a typical interaction radius, ϕ is the azimuthal angle of the three-momentum transfer. The parameters $C_{\Delta\lambda}$ depend on the mass of the diffractive system and the values of R and a define the form of the profile function. The need for non-negligible helicity-flip terms is dictated by the absence in the differential cross-sections [3-5] of the very deep minima predicted by the $\Delta\lambda = 0$ term in eq. (1).

The second class of amplitudes [6], which represents a simpler and more intuitive description of the diffractive differential cross-section, is characterized, on the other hand, by having *i) a non-zero real part, ii) only helicity-conserving terms and iii) a central profile in b-space*. Also this production amplitude is directly determined from nucleon-nucleon experiments [3-5]. To take into account the structure of the cross-section visible in the latest experimental data, it is parametrized in terms of two exponentials:

$$T(t) = i[a_1 e^{b_1 t} + a_2 e^{b_2 t} e^{i\phi}] \quad (3)$$

In this case the overlap function is composed of two terms, of which the one corresponding to the real part is central and the one corresponding to the imaginary part is peripheral. The nucleon-nucleon diffractive data display very little structure, even in the low-mass bins, which implies that the overlap function corresponding to the amplitude (3) is effectively central and mostly Gaussian in b -space.

A specific case of low-mass coherent production is shown in fig. 1a for neutron diffraction on deuterons. The solid curve is the prediction of the Glauber model using the amplitudes (1). While in the original model [2], the form of the

mass dependence of the coefficients $C_{\Delta\lambda}$ is imposed, in order to satisfy an approximate spin-mass correlation, we kept these coefficients as free parameters in our analysis. From a fit to the form (2) of low-mass two-body nucleon diffraction ISR data [3] we obtain a natural damping in $\Delta\lambda$ of the integrated helicity-flip contributions in eq. (2) as given in table 1, where we show the quantity

$$P_{\Delta\lambda} = \frac{\int |T_{\Delta\lambda}(t)|^2 dt}{\int |T_0(t)|^2 dt} \quad (4)$$

as a function of $\Delta\lambda$. This quantity, which represents the relative weight of each helicity-flip contribution to the cross-section, turns out to be similarly damped in $\Delta\lambda$ in all other cases. This damping is a fundamental requirement to get a non-zero asymptotic value for the slope-mass correlation of diffraction dissociation.

The dotted curve in fig. 1a is the result of the same Glauber calculation using as input the amplitude (3). It is clear that this approach is not adequate to describe the data in the interference region. This is made more evident in fig. 1b, where we show the same data and curves, normalized to the theory of the central case (3). The peripheral description of the diffraction mechanism given by amplitudes (1), yields a very good description of the observed complex interference behaviour with respect to the simpler exponential parametrization (3).

The intermediate curves in figs. 1a and 1b are the results of an input amplitude of the form [7]

$$T(t) = iAJ_0(R\sqrt{-t}) e^{\alpha t} + B e^{\beta t} . \quad (5)$$

This helicity-conserving form, with a non-zero real part and a dominant J_0 term singled out, was chosen as an example of a solution with properties which are intermediate between cases (1) and (3). Even this approach yields a negative result.

For the sake of completeness, a last class of models can be considered, which can describe several features of the inelastic diffraction, namely the so-called Deck models. The latest extended version of this model, including absorption effects [8], shows substantial disagreement [9], with the experimental nucleon --

diffraction data at intermediate t -values, and is therefore ruled out as input amplitude for our calculation.

The large differences displayed by the two basic approaches, which appear in fig. 1, are caused by a delicate interplay between the structure of the input amplitude and the properties of interference between single and double scattering, which are typical of the deuteron. This results in a strong constructive interference effect in the data around $-t = 0.3 \text{ GeV}^2$. The corresponding mechanism of interference is shown in fig. 2 for the two different cases of amplitudes (1) and (3). In this figure we show the structure of the imaginary parts of the single- and double-scattering terms for the dominating $\Delta\lambda = 0$ amplitude. Since the argument of the double-scattering term is scaled by a factor of two with respect to the single scattering, the corresponding zeros of the amplitude are displaced on the t scale. This fact explains the constructive interference seen in figs. 1a and 1b, where the large difference between the two input amplitudes is due both to the difference in absolute value of the imaginary parts and to a slight displacement of the relative position of the zeros. The relevance of this constructive interference mechanism in reproducing the data is given by the weight of the $\Delta\lambda = 0$ term for case (1) and of the imaginary part for case (3). This is shown in fig. 3, where the relative weights of these contributions are given for the two types of amplitudes. Figure 3a shows in fact for case (1) that the $\Delta\lambda = 0$ term is very large in the t -region, where the constructive interference takes place. On the other hand fig. 3b shows that only a relatively small contribution of the imaginary part is present in the same region of four-momentum transfer.

The class of amplitudes of type (1) has a natural physical interpretation in terms of the spatial extension of the diffractive systems. It is in fact known from nuclear physics [10] that a non-spherical generalization of the optical potential can describe inelastic scattering in the presence of surface deformation of the excited systems. This can be described in the optical picture by inserting a deformation function $\delta(\phi)$ in the Fraunhofer amplitude:

$$T(t) = \frac{i}{2\sqrt{\pi}} \int_0^{2\pi} d\phi \int_0^{R+\delta(\phi)} b db e^{-ib\sqrt{-t} \cos \phi} \quad (6)$$

$$\delta(\phi) \sim \sum \xi_{\ell m} Y_{\ell m}^* \left(\frac{\pi}{2}, \phi \right) .$$

This gives rise to an elastic differential cross-section proportional to $|J_1(R\sqrt{-t})/R\sqrt{-t}|^2$ and, for the inelastic part, to an expansion over final states having spin corresponding to the excitation multipole:

$$\frac{d\sigma}{dt}_{inel} \sim \sum_{\ell} c_{\ell}(\xi) \sum_{m=-\ell}^{\ell} a_{\ell m} |J_m(R\sqrt{-t})|^2, \quad (7)$$

where $c_{\ell}(\xi)$ are reduced matrix elements squared of the ξ operators, which enter into the definition of the surface deformation. The only difference between formulae (2) and (7) is the modulating exponential in formula (1), which represents the transition from a classical sharp surface of radius $R + \delta(\phi)$, to a smoothly varying profile function, with the same average radius.

The description of diffractive states in terms of spin-dependent deformations would naturally explain a mass dependence of the rescattering cross-section of excited hadronic systems [1, 11]. This interpretation arises naturally from quark confinement theories, in which the various nucleon isobars may be deformed from sphericity, with the shapes of the nucleon excitations varying systematically with mass [12]. This deformation appears dramatically for non-diffractive states, in a geometrical model [13] for high-energy hadronic interactions.

To summarize, the peculiar interference effect observed in high-energy coherent nucleon diffraction on deuterons is very sensitive to both the zeros of the elementary nucleon diffractive amplitude and to the presence of a real part. In the light of this, the deuteron structure can be considered as a very powerful interferometer for hadronic states. An expansion in terms of Bessel functions describing helicity-flip amplitudes appears to be the only functional form for diffractive production which can account for the observed effect. In the extreme optical limit, this is equivalent to describing high-energy collisions with

non-spherical particles, the diffractive inelastic excitations being rotational states of deformed objects. This picture is typical of collective excitations of composite systems and is therefore a natural feature of quark confinement theories.

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Table 1

Helicity-flip dependence of the quantity $P_{\Delta\lambda}$, the relative weight of each helicity-flip contribution to the cross-section, for the reaction $pp \rightarrow (n\pi^+)p$, $1.3 < m_{n\pi^+} < 1.4$ GeV

$\Delta\lambda$	0	1	2	3	4
$P_{\Delta\lambda}$	1	0.263	0.125	0.015	5×10^{-5}

Figure captions

- Fig. 1 : a) Differential cross-sections of two-body coherent diffraction of neutrons on deuterons at $\sqrt{s} = 37$ GeV for $1.3 \leq m_{p\pi^-} \leq 1.44$ GeV. The solid curve is the result of a Glauber calculation with purely imaginary helicity-flip amplitudes [eq. (1)]. The dashed curve is a similar calculation for a helicity-conserving exponential amplitude with non-zero real part [eq. (3)]. The dotted line is an intermediate case described in the text [eq. (5)].
- b) The same as in fig. 1a normalized to the helicity-conserving exponential case [eq. (3)].
- Fig. 2 : a) The imaginary part of the single- and double-scattering amplitudes for the dominant $\Delta\lambda = 0$ term in the helicity-flip expansion [eq. (1)].
- b) The same as in fig. 2a for the helicity-conserving exponential amplitude given by eq. (3).
- Fig. 3 : a) Helicity-non-flip and helicity-flip contributions to the differential cross-section for the input amplitude (1), as a function of t .
- b) Real and imaginary part contributions to the differential cross-section for the input amplitude (3), as a function of t .

Fig. 1

Fig. 2

Fig. 3