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ORIGIN OF THE N* (1150) ENHANCEMENT AND THE d*(2200) EFFECT

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Using pion exchange and $\Delta(1236)$ excitation inside the deuteron, the N*(1150) enhancement with isospin $I=\frac{1}{2}$, seen in evidence in dp coherent interactions, is explained. Good agreement is obtained, without any arbitrary normalization, between the Frascati-Caen-Saclay data and the predictions of this model. Its leading features and applications to other experiments are given.

The dp coherent interaction

$$\mathrm{dp} \to \mathrm{dX} \tag{1}$$

has been studied by a Caen, Frascati, Saclay collaboration [1], using a missing mass method. A relevant feature of this process is that the baryonic system is in a pure $I=\frac{1}{2}$ isospin state. The experimental data show two clear enhancements for the X system in the regions around the masses of 1350 MeV/c^2 and 1150 MeV/c^2. The first one, associated with highest momentum transfers, may be interpreted as single-pion production with formation of the outgoing deuteron by the proton target and a nucleon of the incident deuteron (fig. 1a). The kinematical position, integrated cross section and behaviour of the experimental peak with momentum transfer are roughly in agreement with the general features of this baryon exchange mechanism [2]. The structure of the X system close to the 1150 MeV/c^2 mass is less easy to interpret. The momentum transfer is sufficiently small, so that a really coherent interaction is expected, the incoming and outgoing deuterons being the same.

No baryonic resonance at 1150 MeV/c^2 ($I=\frac{1}{2}$) has been observed by phase-shift analysis [3]. However, we notice that diffractive phenomena can give rise to enhancements in the low-mass regions [4]. There are experimental evidences, for example, in $\mathrm{K^-p} \to \bar{\mathrm{K}}\pi\mathrm{N}$ and $\mathrm{K^-p} \to \bar{\mathrm{K}}^*(890)\pi\mathrm{N}$ at 10 GeV/c [5], in $\pi^\pm\mathrm{p} \to \pi(\mathrm{N}\pi)$ at 8 GeV/c and at 16 GeV/c [6]. The existence of an N* enhancement, $I=\frac{1}{2}$ below 1400 MeV/c^2, has been also revealed by isospin analysis of the Nπ final state in the pp, pn and pd interactions [7]. Even observed enhancement in the $\mathrm{dp} \to \mathrm{dX}$ process at a mass of 1150 MeV/c^2, varying with momentum transfer as the elastic scattering, has been classified as diffractive excitation [8]. In a diffractive excitation a pomeron

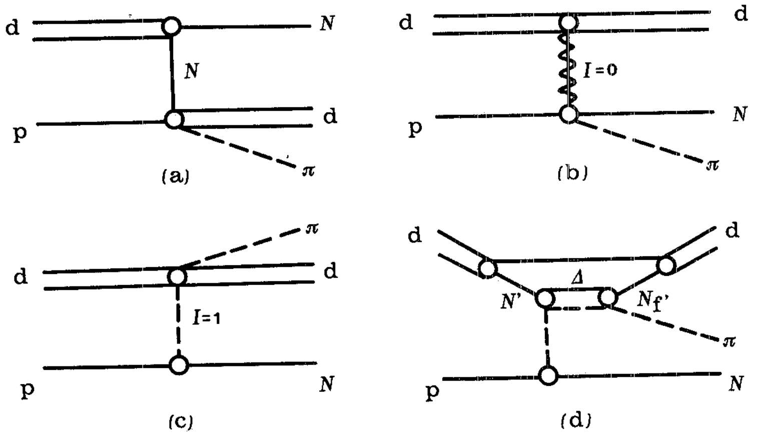

Fig. 1. Possible mechanisms for the dp → dNπ process.

is exchanged in the t-channel (fig. 1b). Alternatively, we can try to explain the observed Nπ bump by a Deck-like effect, relating it to a dπ effective enhancement with a pion exchanged in the t-channel (fig. 1c). A Δ(1236) is excited inside the incoming deuteron: coherence requires that the nucleon arising by the Δ decay remains bound in the deuteron (fig. 1d). In this way a dπ enhancement is produced close to the NΔ mass (2.2 GeV/c^2) and it reflects in a bump at the Nπ kinematical threshold [9]. Indeed, many experiments, performed with different projectiles on a deuteron target over a large range of energy, observe a clear bump, the so-called d* effect, around a mass of ~2.2 GeV/c^2 in the dπ system [10].

We apply our model to explain the N*(1150) bump observed in the dp coherent reaction (1) and, moreover, we test the proposed mechanism on the bulk of the experimental available data on the d* effects. The idea of an internal excitation of the deuteron like the upper box of our graph has been first suggested by Month [11] to emphasize the Δ(1236) role in the deuteron Compton scattering. Various models [12] have been suggested to explain the d*. However, they provide only shape and position of the enhancement. By our approach the cross section of the dp coherent interaction (1) can be achieved furthermore without any arbitrary normalization.

We have treated the process

$$\mathrm{dp} \to (\mathrm{d}\pi)\mathrm{N}$$

in the impulse approximation, considering only to first order the interaction between the nucleons in the deuteron and the proton target. The matrix element has been estimated in the reference frame where the deuteron is at rest, using the well-known non-relativistic deuteron wave function. Indeed, this frame, for 2.95 GeV/c incident deuterons, is not substantially different from the more appropriate Breit reference system [13]. We verified that this choice produces effects on the peak cross section less than 5%. The reaction amplitude, as usual in impulse approximation, is given by:

$$\langle \mathrm{f}|T_\mathrm{d}|\mathrm{i}\rangle = \int \mathrm{d}^3p_\mathrm{r} C^*(\boldsymbol{p}_\mathrm{r}) \{\langle \boldsymbol{p}_\pi, \boldsymbol{p}_\mathrm{N}, \tfrac{1}{2}\boldsymbol{p}_\mathrm{d} + \boldsymbol{p}_\mathrm{r}|T_\mathrm{p}|\boldsymbol{p}_\mathrm{i}, -\tfrac{1}{2}\boldsymbol{p}_\mathrm{d} + \boldsymbol{p}_\mathrm{r}\rangle C(\tfrac{1}{2}\boldsymbol{p}_\mathrm{d} - \boldsymbol{p}_\mathrm{r})$$

$$+ \langle \boldsymbol{p}_\pi, \boldsymbol{p}_\mathrm{N}, \tfrac{1}{2}\boldsymbol{p}_\mathrm{d} - \boldsymbol{p}_\mathrm{r}|T_\mathrm{n}|\boldsymbol{p}_\mathrm{i}, -\tfrac{1}{2}\boldsymbol{p}_\mathrm{d} - \boldsymbol{p}_\mathrm{r}\rangle C(\tfrac{1}{2}\boldsymbol{p}_\mathrm{d} + \boldsymbol{p}_\mathrm{r})\} ,$$

where T_p, T_n are the transition operators for the nucleons in the deuteron and $C(\boldsymbol{p}_\mathrm{r})$ is the Fourier transform of the deuteron wave function. The amplitude has been factorized in a product between the deuteron form factor and the production amplitude on the nucleon. This one, being an unsmooth function of $\boldsymbol{p}_\mathrm{r}$, has been calculated at $\boldsymbol{p}_\mathrm{r} = \pm\frac{1}{4}\boldsymbol{p}_\mathrm{d}$, where the product $C^*(\boldsymbol{p}_\mathrm{r})C(\frac{1}{2}\boldsymbol{p}_\mathrm{d} \mp \boldsymbol{p}_\mathrm{r})$ is the highest. In the energy and momentum transfer range of the considered dp experiment the single pion production amplitude on a nucleon is well described by one-pion exchange and $\Delta(1236)$ excitation [14]. In the deuteron the helicity of the resonance is assumed the same of the excited nucleon, so that the spin-flip and non-spin-flip contributions can be separated. Taking into account S and D components of the deuteron wave function we may write

$$|\langle \mathrm{f}|T_\mathrm{d}|\mathrm{i}\rangle|^2 = |g|^2 (G_0^2 + 2G_2^2) + \tfrac{2}{3}|h|^2 (G_0 - \tfrac{1}{2}G_2)^2 ,$$

where g and h indicate the non-spin-flip and spin-flip amplitudes, respectively. For G_0, charge deuteron form factor, and G_2, quadrupole form factor, we used the same parametrization utilized by Bertocchi [13]:

$$G_0(q^2) = \sum_i A_\mathrm{i}\, \mathrm{e}^{-\alpha_i q^2} , \qquad G_2(q^2) = q^2 \sum_i B_i\, \mathrm{e}^{-\beta_i q^2} .$$

Resonance excitation allows us to correlate π^0 and π^+ production amplitudes on the proton and neutron, using respective isospin coefficients. Finally, the elementary amplitude has been calculated, following Selleri [14], putting the exchanged pion on the mass shell and using π^+p scattering data [15]. In our matrix element all the exchanged particles are taken on the mass shell. By the Lovelace method for resonant amplitudes [16], we evaluated that off-mass shell effects change the peak cross sections by 10%, at most [2].

The complete expression of the cross section is:

$$\mathrm{d}\sigma = \frac{2G_\mathrm{r}^2}{3\pi^4 M_\mathrm{N}^2} \frac{W^2}{p_i^2} \frac{t}{(t + m_\pi^2)^2}\, p_i^{**} W_\mathrm{T} \frac{E_{\mathrm{d}_\mathrm{f}}}{E_{\mathrm{N}'_\mathrm{f}}} \sigma[(G_0^2 + 2G_2^2)\cos^2\theta^*$$

$$+ \tfrac{1}{6}(G_0 - \tfrac{1}{2}G_2)^2 \sin^2\theta^*] \frac{\mathrm{d}^3p_\mathrm{d}\,\mathrm{d}^3p_\mathrm{N}\,\mathrm{d}^3p_\pi}{2E_\mathrm{d}2E_\mathrm{N}2E_\pi} \delta^4(P_\mathrm{i} - P_\mathrm{f}) ,$$

where $\sqrt{2}G_\mathrm{r}$ is the rationalized and renormalized coupling constant for emission of a charged pion, W_T the total energy in the c.m. system, t the square of the four-momentum transfer between the proton and the outgoing nucleon. The values of p_i, $E_{\mathrm{d_f}}$, $E_{\mathrm{N'_f}}$ are calculated in the reference frame in which the initial deuteron is at rest; they are, respectively, the incident proton momentum, the final deuteron energy and the energy of the nucleon $\mathrm{N'_f}$ coming from Δ decay. W is the $\pi\mathrm{N'_f}$ invariant mass and θ^* is the pion angle in the Δ system; p_i^{**} is the momentum in the c.m. of the pN′ subsystem.

This approach gives an absolute prediction for the cross section and no further normalization is introduced to compare calculations and experimental results. The predictions of the model, together with the experimental data on the dp → dX reaction, at 2.95 GeV/c [1], are shown in fig. 2. The enhancement at 1150 MeV/c^2 in the Nπ invariant mass is very well reproduced in behaviour and absolute value at $\theta_\mathrm{d}^\mathrm{lab} = 4.6°$. Also at $\theta_\mathrm{d}^\mathrm{lab} = 7.4°$ the agreement is satisfactory, while at $\theta_\mathrm{d}^\mathrm{lab} = 10.2°$ the calculated cross section is compromised by the assumed approximations. As expected, the proposed model is more suitable at small momentum transfers, while at large momentum transfers all the neglected corrections play a larger role: mainly multiple scattering corrections, interference and contribution of baryon exchange (fig. 1a), many particle exchange in the nucleon-nucleon matrix element, two-

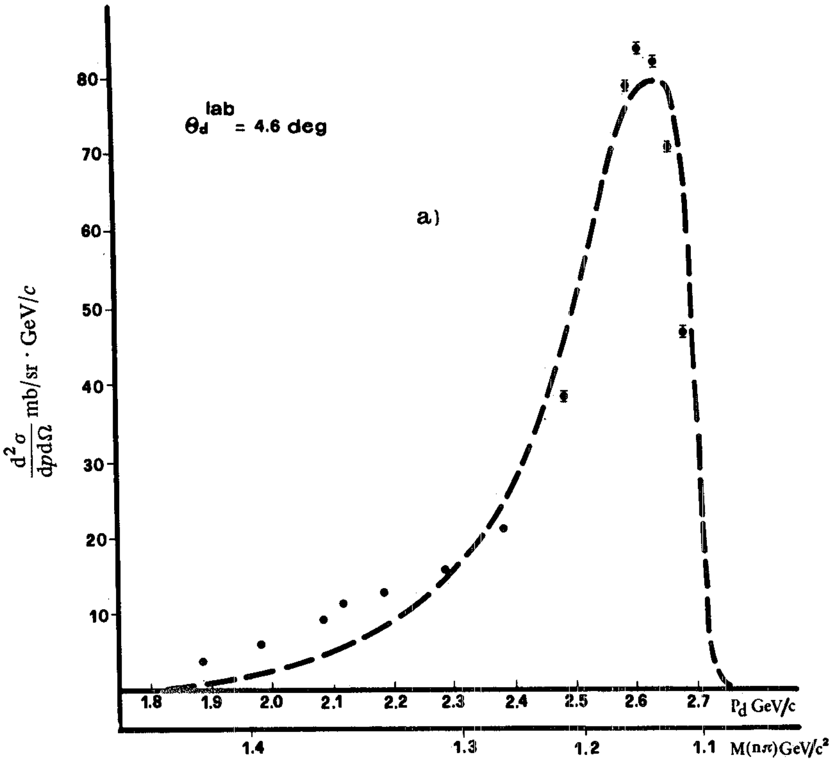

Fig. 2.

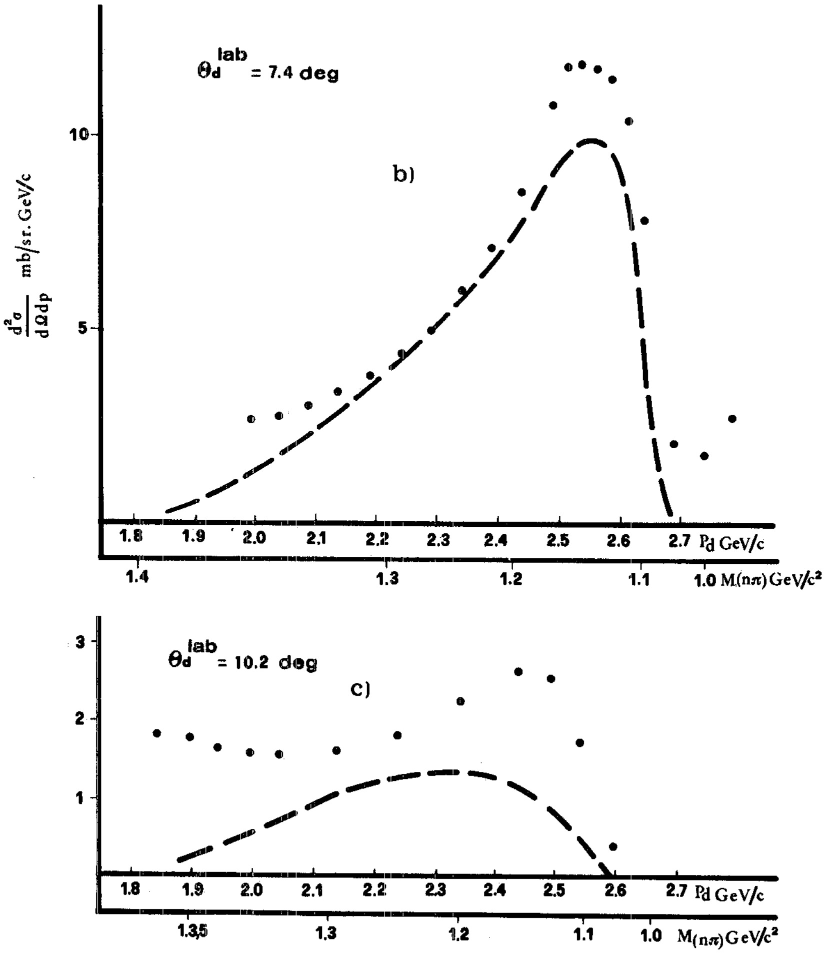

Fig. 2. Lab momentum distributions of scattered deuterons for dp → dX at 2.95 GeV/c: experimental data (●) of Caen-Saclay-Frascati collaboration [1] and predictions of model (dashed lines). A scale shows the invariant mass of the X system.

pion contribution, etc. Furthermore the cross section becomes small and any experimental background becomes relatively more important.

Afterwards, for testing more generally the validity of the model, we have tried to reproduce the behaviour of the d* enhancement in the dπ invariant mass, observed in many experiments with several kind of projectiles [10, 17, 18]. In table 1 we compare the experimental d* masses and widths with the calculated ones. As it is shown, an overall agreement is achieved. The πd bump, suspected as a $I = 1$ resonance [18], is also well explained within this model.

For a more quantitative comparison we have examined in detail the $\bar{p}d \to d\bar{n}\ \pi^-$

Table 1
Experimental and calculated masses and widths for the $d\pi$ enhancement in various reactions

Reactions and references	Incident particle momentum (GeV/c)	s (GeV)^2	$M_{d\pi}$ (GeV/c^2)		$\Gamma_{d\pi}$(GeV/c^2)		Model [a]
			experimental	calculated	experimental	calculated	
$pd \to nd\pi^+$ [18]	1.54	11.1	2.180	2.16	0.09	0.11	$pd \to nd^{*+}$
$pd \to nd\pi^+$ [10m]	1.825	12.1	2.15	2.16	0.18	0.13	$pd \to nd^{*+}$
$pd \to pd\pi^+\pi^-$ [10d]	1.825	12.1	2.125 ± 0.010	2.15	0.050 ± 0.010	0.13	$pd \to \Delta^{++}d^{*-}$
$K^+d \to K^+d\pi^-\pi^+$ [10f]	3.0	15.2	~2.20	2.15	~0.16	0.16	$K^+d \to d^{*+}(K\pi)_{IPS}$
$\pi^-d \to \pi^-d\pi^-\pi^+$ [10a]	3.7	16.7	2.170	2.17	0.100	0.14	$\pi^-d \to \rho^0 d^{*-}$
$K^-d \to K^-d\pi^+\pi^-$ [10e]	5.5	24.5	2.200	2.17	0.150	0.18	$K^-d \to d^{*-}K^*$
$\bar{p}d \to \bar{p}d\pi^-\pi^+$ [10g]	5.55	25.5	2.19 ± 0.01	2.18	0.18 ± 0.02	0.14	$\bar{p}d \to d^{*+}\bar{\Delta}^{--}$
$\bar{p}d \to \bar{n}d\pi^-$ [17]	5.55	25.5	2.16 ± 0.01	2.14	0.16 ± 0.04	0.14	$\bar{p}d \to \bar{n}d^{*-}$
$\pi^+d \to \pi^+d\pi^+\pi^-$ [10c]	6.0	26.0	2.15	2.15	~0.15	0.15	$\pi^+d \to d^{*+}(2\pi)_{IPS}$

The uncertainties of the calculated $M_{d\pi}$ and $\Gamma_{d\pi}$ are about 10 MeV/c^2. In reactions [10f] and [10c] the symbol ~ indicates a rough estimate made from published histograms. In the process [10d], for which high t-values have been considered, the experimental low value of the $d\pi$ mass cannot be explained by a Δ excitation in the deuteron, but probably by nucleon exchange, as suggested by the narrow width. The symbols d^{*+} and d^{*-} indicate respectively $d\pi^+$ and $d\pi^-$ systems.

[a] Reactions, in which two pions were produced, have been assumed to be dominated by d^* and by excitation of the incident particle or IPS distribution.

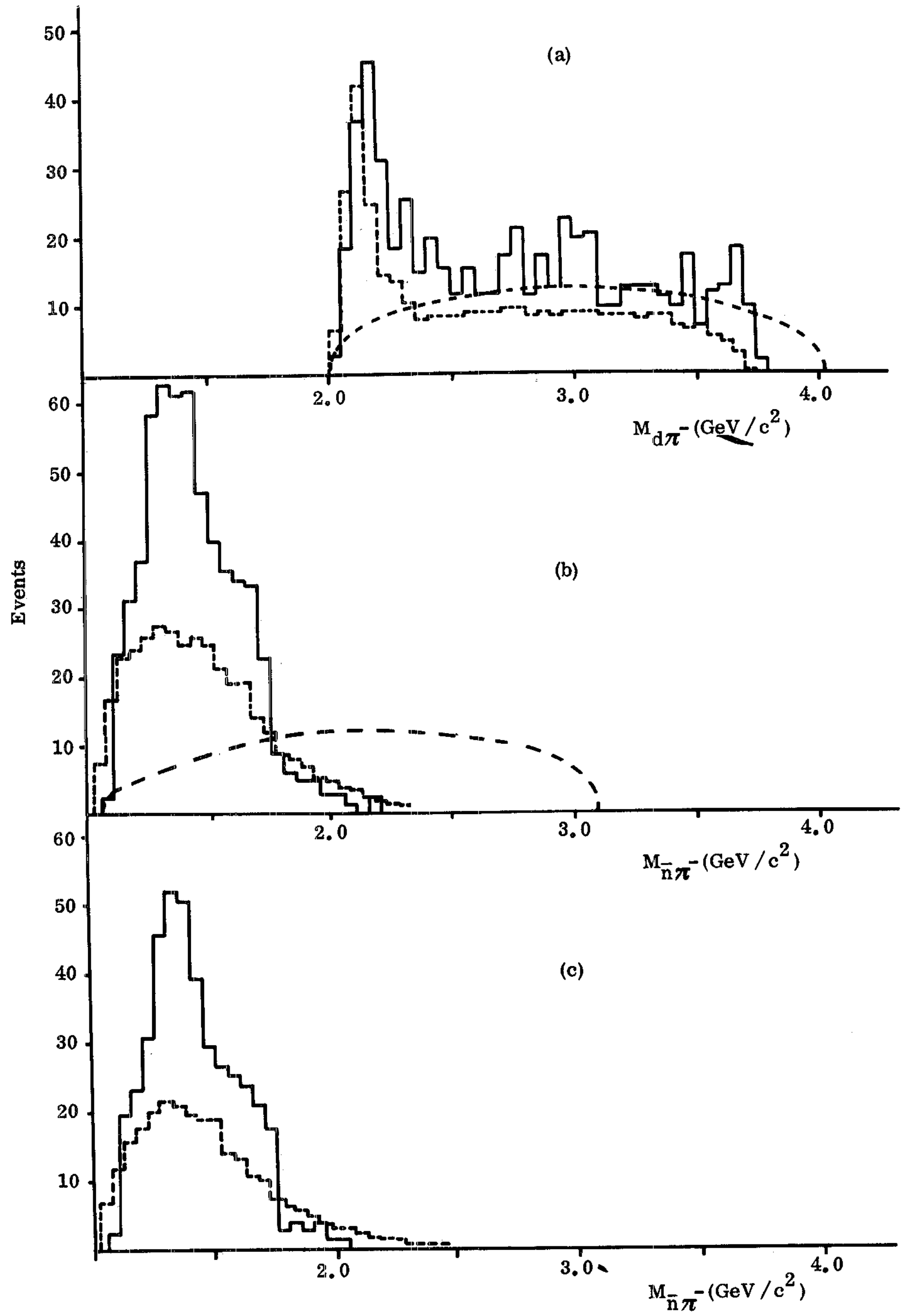

Fig. 3. $M_{d\pi^-}$ and $M_{\bar{n}\pi^-}$ distributions for $\bar{p}d \to d\bar{n}\pi^-$ at 5.55 GeV/c. (a) $M_{d\pi^-}$ distribution. Solid histogram corresponds to experimental data as given by ref. [17]; the dashed one represents the d*− model prediction and the dashed line shows the phase-space behaviour. (b) $M_{\bar{n}\pi^-}$ distribution. Histograms and the lines have the aforementioned meanings. (c) $M_{\bar{n}\pi^-}$ distribution for $M_{d\pi^-} > 2.3$ GeV/c^2: experimental data and predictions. The d* contribution, for $M_{d\pi^-} > 2.3$ GeV/c^2, exhibits a large structure in the $M_{\bar{n}\pi^-}$ mass and still exhausts about 60% of the selected events.

bubble chamber experiment at 5.5 GeV/c [17], in which enhancements were found in dπ^- and $\bar{n}\pi^-$ mass spectra, centered around 2160 MeV/c^2 and 1350 MeV/c^2, respectively. Absolute predictions of dπ^- and $\bar{n}\pi^-$ invariant mass distributions are shown in fig. 3. The bump in the dπ^- invariant mass is well reproduced. Conversely, the so-called N*(1300) enhancement in the $\bar{n}\pi^-$ invariant mass is not completely exhausted by d* contribution. In the experiment paper, the authors looked at the $\bar{n}\pi^-$ invariant mass spectrum, cutting the events with $M_{d\pi^-} < 2.3$ GeV/c^2, to reduce the d* contribution. The comparison between the resulting spectrum and the prediction of our model, with the same cut, is shown in fig. 3c. Still about 60% of the total events is expected by the d* mechanism in a large structure. The remaining excess of events suggests other mechanisms, to be explained, like $\bar{p}$ diffractive excitation or N*(1470) production.

In conclusion, our model, in the limits of its applicability, gives a satisfactory prevision for the behaviour of the observed bump in the reaction dp → dX at 2.95 GeV/c. A very good agreement is reached in the cross-section evaluation without any arbitrary normalization. Moreover, it reproduces many features of d* enhancement for a large range of energies and for different reactions; in the $\bar{p}d \rightarrow \bar{n}\pi^- d$ reaction it gives predictions able to isolate the residual diffractive excitation.

We point out that further investigations about these effects could be realized by studying the reaction ^{4}He p → ^{4}He X where again the X system is in a pure isospin state $I = \frac{1}{2}$, or studying deuteron polarization effects. A polarized deuteron beam, as now available, can be an experimental facility for this purpose [19].

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