Projectile Δ and target Roper excitation in the $p(d,d')X$ reaction

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In this paper we compare a model that contains the mechanisms of Δ excitation in the projectile and Roper excitation in the target with experimental data from two (d,d') experiments on a proton target. The agreement of the theory with the experiment is fair for the data taken at $T_d=2.3$ GeV. The Δ excitation in the projectile is predicted close to the observed energy with the correct width. The theory, however, underpredicts by about 40% the cross sections measured at T_d = 1.6 GeV at angles where the cross section has fallen by about two orders of magnitude. The analysis done here allows us to extract an approximate strength for the excitation of the Roper [$N^*(1440)$] excitation and a qualitative agreement with the theoretical predictions is also found.

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I. INTRODUCTION

The (α,α') reaction on a proton target measured at Saclay [1] has been instrumental in setting the question of the mechanism of Δ excitation in the projectile (DEP), which was introduced in Ref. [2] in order to describe the $(^3\mathrm{He},t)$ reaction in p and d targets [3]. That mechanism plays a negligible role in the $(^3\mathrm{He},t)$ reaction on proton targets but is quite important in the same reaction on neutron targets and was predicted to be dominant in the $(^3\mathrm{He},^3\mathrm{He})$ reaction on proton and neutron targets [4]. Prior to the (α,α') experiment the relevance of the DEP mechanism was a subject of debate [5,6], particularly because of the small strength of this mechanism in the $(^3\mathrm{He},t)$ reaction on proton targets, which allowed interpretations omitting it [7,8]. The (α,α') reaction on a proton target is ideal to isolate the DEP mechanism since, because of isospin, the Δ excitation on the proton target is forbidden. This allowed us to test the ideas introduced in Ref. [2] and indeed the large peak in the experiment [1] corresponding to DEP was well reproduced [9].

In addition to the issues discussed above, the (α,α') experiment [1] observed a smaller peak at higher excitation energies which was attributed to the Roper excitation. This mode of excitation of the Roper is novel, since it involves an isoscalar source, and can be relevant in determining the strength of three body forces [10] and providing new tools for the comprehension of the $NN\rightarrow NN\pi\pi$ and related reactions [11].

The strength of the isoscalar $NN\rightarrow NN^*$ transition was determined empirically from the experimental data in Ref. [12], where the model of Ref. [9] for DEP was used and the interference of the two mechanisms was also considered. The analysis proved consistent with the present knowledge of position, decay width and partial decay widths of the Roper and helped to narrow the experimental uncertainties on these magnitudes.

The issue of strong isoscalar excitation of nucleon resonances has captured more attention after the first inclusive $(\vec{d},d')$ data were obtained [13]. The T_{20} data obtained at Dubna on the proton and ^{12}C, are given in Ref. [14] and the final data tables are published in Ref. [15]. In Ref. [16] polarization observables for the $(\vec{d},d')$ reaction on proton targets are discussed bringing new information on electromagnetic form factors of the deuteron and on mechanisms for strong excitation of nucleonic resonances. The description done in Ref. [12] was extended to higher energies of around 10–15 GeV [17], showing that the magnitude of the Roper excitation can be increased by about one order of magnitude and the relative strength of the Roper signal to the one of the DEP mechanism becomes of the order of unity, much bigger than in the (α,α') experiment [1] where it is about 1/4. In Ref. [18] polarization observables in the $(\vec{p},\vec{p}')$ on a ^{4}He target are studied with its view towards possible experiments to be carried out at the Indiana Cyclotron.

The program of nucleon resonance excitation using baryonic interactions is thus catching up, and certainly will bring complementary information to the one obtained with electromagnetic probes or meson induced excitation.

The present work, DEP and Roper excitation on the (d,d') reaction on proton targets, should be considered as a complement to the one of the (α,α') reaction [12]. The fact that the deuteron has an isospin $I=0$ makes the two works similar since Δ excitation on the proton target is forbidden in both cases and only DEP and Roper excitation are allowed in the region which we study. However, the fact that the deuteron has a total spin $J=1$ induces some differences with respect to the (α,α') reaction and sets different constraints on the theoretical models. With new experiments on this issue coming, the need to have reliable theoretical models to extract the relevant information becomes apparent, and in this sense our present work is a valuable one. We have taken advantage of the existence of experimental information from Saclay measurements of the (d,d') reaction and we present here a paper where the theoretical ideas are exposed, the data are presented and a discussion is made from comparison of theory and experiment.

Early work on the present reaction at different kinematics is done in Ref [19]. We will compare the theoretical results

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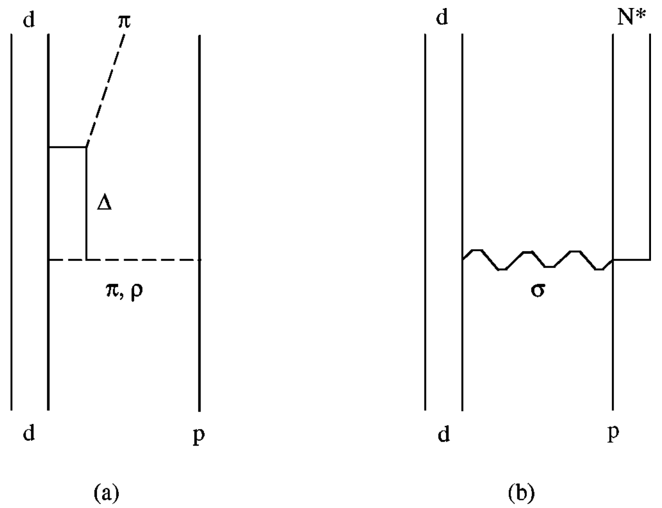

FIG. 1. Diagrams for the $p(d,d')X$ reactions considered in this paper. They are (a) the Δ excitation in the deuteron and (b) the Roper excitation in the proton. The σ exchange must be interpreted as an effective interaction in the isoscalar exchange channel [12].

of the model with recent (d,d') measurements done at Saclay [20] and older (d,d') measurements [21] done at lower energies and larger angles.

II. FORMULATION

In this section we consider a theoretical model of the (d,d') reaction on the proton target. We include two processes, Δ excitation in the projectile and Roper excitation in the target, which are shown in Fig. 1 and are the dominant processes in this energy region [12]. We include both the πN and $2\pi N$ decay modes of the Roper resonance. Since we need to take care of the interference between the projectile Δ process and the target Roper process decaying into πN, we treat the Roper $\to \pi N$ and Roper $\to 2\pi N$ processes separately. We take the same model which was used to analyze the (α,α') reaction at 4.2 GeV and use the same values for all parameters [12].

The cross section for the 1π decay Δ and Roper processes is given by

$$\frac{d^2\sigma}{dE_{d'}d\Omega_{d'}} = \frac{p'_d}{(2\pi)^5}\frac{M_d^2 M^2}{\lambda^{1/2}(s,M^2,M_d^2)}\int d^3p_\pi \frac{1}{E'_N\omega_\pi} \times \overline{\sum}\sum |T^{1\pi}|^2 \delta(E_d+E_N-E'_d-E'_N-\omega_\pi), \tag{1}$$

where λ $(\cdots)$ is the Källen function and s the Mandelstam variable for the initial p-d system, and momentum conservation, $\vec p_d+\vec p_N=\vec p'_d+\vec p'_N+\vec p_\pi$ is already implied. The projectile Δ mechanism (T_Δ) leads to a πN through the decay of the Δ. Part of the Roper excitation mechanism leads to the same final state through the decay of the N^* into πN. We call this latter piece $T_*^{1\pi}$. Hence the sum of the two mechanisms leading to πN is given by

$$T^{1\pi} = T_\Delta + T_*^{1\pi}. \tag{2}$$

The nucleon and deuteron spin sum and average of each $|T|^2$ and plus the interference term can be written as

$$\overline{\sum}\sum |T_\Delta|^2 = \frac{16}{27}F_d^2\left(\frac{f^*}{\mu}\right)^4\left(\frac{f}{\mu}\right)^2 |G_\Delta|^2\left(\frac{-q^2}{\vec q^2}\right)[(V_{l'}^2+5V_{t'}^2)\vec p_\Delta^2 + 3(V_{l'}^2-V_{t'}^2)(\vec p_\Delta\cdot\hat q)^2], \tag{3}$$

$$\overline{\sum}\sum |T_*^{1\pi}|^2 = 12F_d^2\left(\frac{f'}{\mu}\right)^2 g_{\sigma NN}^2 g_{\sigma NN^*}^2 |G_*|^2 |D_\sigma F_\sigma^2|^2 \vec p_*^2, \tag{4}$$

$$\overline{\sum}\sum (T_*^{1\pi *}T_\Delta + T_\Delta^* T_*^{1\pi}) = 2\,\mathrm{Re}\left\{\frac{16}{3}F_d^2\frac{f'}{\mu}\left(\frac{f^*}{\mu}\right)^2\frac{f}{\mu}g_{\sigma NN}g_{\sigma NN^*}D_\sigma^* G_*^* G_\Delta F_\sigma^2 \times [V_{l'}(\vec p_*\cdot\hat q)(\vec p_\Delta\cdot\hat q) + V_{t'}(\vec p_*\cdot\vec p_\Delta - (\vec p_*\cdot\hat q) \times (\vec p_\Delta\cdot\hat q))]\right\}\sqrt{\frac{-q^2}{\vec q^2}}, \tag{5}$$

where G_Δ and G_* are the propagators of the Δ and Roper resonances, D_σ the propagator of the σ meson, F_σ the σNN vertex form factor. The momenta $\vec p_*, \vec p_\Delta$, and $\vec q$ are the pion momenta in the Roper rest frame, pion momentum in the Δ rest frame, and momentum transfer between the nucleons, respectively. $V_{l'}$ and $V_{t'}$ stand for the longitudinal and transverse parts of $NN\to N\Delta$ effective interaction which includes π, ρ, and g' contributions, where g' is the Landau-Migdal parameter which is meant to account for short range corrections to the π and ρ exchange. The $f's$ and $g's$ are coupling constants. All details, including parameter values, are shown in Ref. [12].

The function F_d is the deuteron form factor defined as

$$F_d(\vec k) = \int d^3r\,\varphi^*(\vec r)e^{i\vec k\cdot\vec r/2}\varphi(\vec r), \tag{6}$$

where $\varphi(r)$ is the relative wave function of the deuteron obtained from the Bonn potential [22]. The momentum transfer of the deuteron is denoted by $\vec k=\vec p_d-\vec p_{d'}$ taken in the initial deuteron rest frame. We have included only the s-wave part of the deuteron wave function for simplicity. The contribution from the target Roper process decaying into $2\pi N$ is calculated separately as

$$\frac{d^2\sigma}{dE_{d'}d\Omega_{d'}} = \frac{p'_d}{(2\pi)^3}\frac{2M_d^2 M}{\lambda^{1/2}(s,M^2,M_d^2)}\overline{\sum}\sum |T^{\pi\pi}|^2 |G_*|^2 \Gamma_*^{\pi\pi} \tag{7}$$

with

$$\overline{\sum}\sum |T^{\pi\pi}|^2 = 4F_d^2 g_{\sigma NN}^2 g_{\sigma NN^*}^2 |D_\sigma F_\sigma^2|^2 \tag{8}$$

using the partial decay width, $\Gamma_{*}^{\pi\pi}$, whose explicit form is shown in the Appendix of Ref. [12]. This contribution is added to the 1π contributions incoherently.

III. DISCUSSION OF EXPERIMENTAL RESULTS

We compare our theoretical results with two independent experimental data sets. One has been obtained recently at $T_d = 2.3$ GeV at Saturne [20] and another was measured some years ago at $T_d = 1.6$ GeV [21].

First, we consider the new data which were obtained during a short run at Saturne with a deuteron beam of 2.3 GeV. The deuterons were directed onto a 4 cm thick liquid hydrogen target with thin Ti windows (15 μm). After going through a 40 cm thick lead collimator, the scattered deuterons were momentum analyzed at very small angles using the SPES4 spectrometer [23] with a momentum acceptance of $\pm 3\%$ and a resolution of $\approx 10^{-3}$. In the focal plane of the spectrometer, the scattered deuterons were detected using the three front wire chambers of the extended vector polarimeter POMME [24].

In this experiment, special care was taken to minimize all possible experimental backgrounds. A missing mass spectrum was measured at 1.1° in five different momentum bites, respectively, centered on 2.6, 2.8, 3.0, 3.2, and 3.45 GeV/c, covering an excitation energy region up to 600 MeV. The spectrometer acceptance is 15% of the central momentum leading to smaller momentum bites for higher excitation energies. In order to get the most out of the limited beam time in terms of number of counts in each bite and range of coverage in excitation energy, the momentum bites were set as follows: two overlapping bites around 200 MeV of excitation energy, where the excitation of the Δ resonance in the projectile is expected, and, three non overlapping bites spanning the excitation energy range from 300 to 600 MeV, where the wide Roper resonance is expected (the kinematical limit is at 680 MeV of excitation energy). The target was located outside of the magnetic field of the spectrometer so the usual SPES4 corrections for correlations between scattering angle and scattered momentum were not necessary.

The cross section spectrum was binned in 10 MeV steps of excitation energy. For each setting of the spectrometer, empty target measurements were taken for background subtraction. The ratio of full to empty target was in the range of 8 to 10 dropping to 2 for the lowest setting of the spectrometer (corresponding to high excitation energies). We could not get clean measurement at momenta smaller than 2.4 GeV/c because of the large background due to rescattering through the lead collimator. When present, this background shows a strong angular dependence; taking into account the shape of the collimator, different cuts on angular acceptance lead to substantial changes in the shape and slope of the spectrum. For all momentum bites shown in Fig. 2, the off-line analysis of full versus empty target spectra and software cuts on angular acceptances showed no changes in the shape of the spectrum; only overall scaling of the spectrum consistent with the changes of the solid angle, were observed. This extensive off-line analysis led to the conclusion that no significant experimental background was present for these momentum bites. Absolute cross sections were determined using monitors calibrated with the Carbon activation method [25]. This is the well tested standard method of normalization used at Saturne.

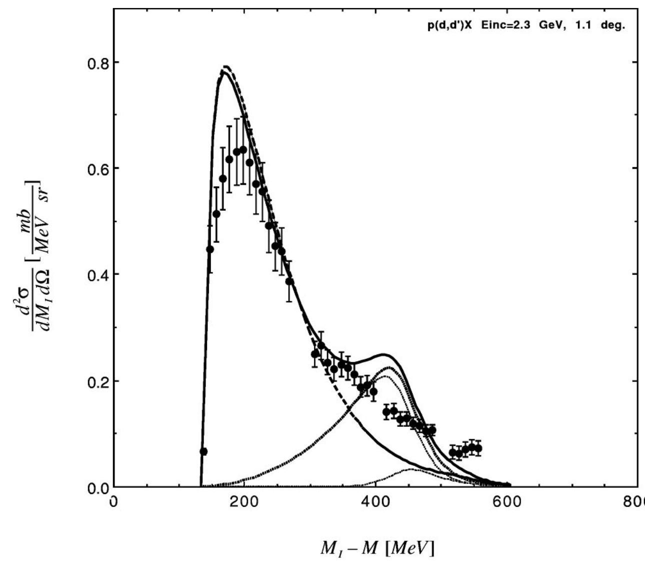

FIG. 2. The double differential cross section $d^2\sigma/dM_I d\Omega$ is shown as a function of excitation energy of the proton. The M_I is the invariant mass of the target system. Solid circles indicate the experimental data obtained in Ref. [20]. The theoretical calculations are also shown in the figure, which are total spectrum (solid line), contribution from Δ excitation (dashed line), and contribution from Roper excitation (thick dotted line). The Roper contributions decaying into πN and $\pi\pi N$ are separately shown as thin dotted lines.

The measured missing mass spectrum shown in Fig. 2 is dominated by a large structure centered around 200 MeV. This structure has been identified as the excitation of the Delta resonance in the incoming deuteron. The cross section drops sharply between 200 and 300 MeV of excitation energy. Between 300 and 600 MeV, there seems to be an excess of cross section above the high energy tail of the Δ resonance. There seems to be a discontinuity in the measured cross section around 500 MeV of excitation energy. This corresponds to the highest excitation energy bite that we can cleanly measure and could be affected by the subtraction of a relatively large empty target contribution.

In Fig. 2, we compare our theoretical results (including all reaction mechanisms described in Sec. II) with these experimental data. We have plotted on the same figures the different curves corresponding to the excitation of the Δ alone, the excitation of the Roper alone and the total cross section taking into account the interference between the two. For the excitation of the Roper, the contributions for the πN and $2\pi N$ channels are also shown. We see that the projectile Δ excitation makes a large contribution to the cross section around 200 MeV. The calculation correctly reproduces the excitation energy of the Δ and its width, however, it overpredicts the cross section at the maximum by at least 20%. The excitation of the Δ in the projectile cannot account for the observed cross section between 300 and 500 MeV. This range of excitation energy is where we are expecting the Roper resonance to be and the calculation indeed predicts

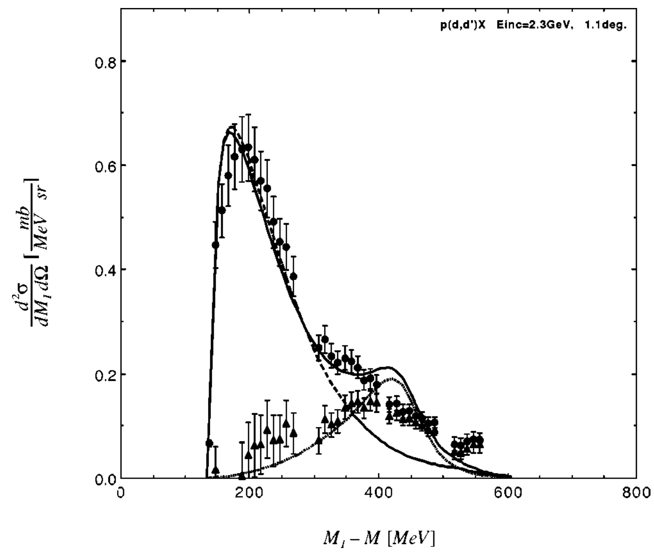

FIG. 3. The double differential cross section $d^2\sigma/dM_I d\Omega$ is shown as a function of excitation energy of the proton. The M_I is the invariant mass of the target system. Solid circles indicate the experimental data obtained in Ref. [20]. The theoretical calculations normalized by a factor of 0.85 are also shown in the figure, which are total spectrum (solid line), contribution from Δ excitation (dashed line), and contribution from Roper excitation (dotted line). Solid triangles are Roper contribution extracted from the data by subtracting the calculated Δ and interference contributions with a normalization factor of 0.85.

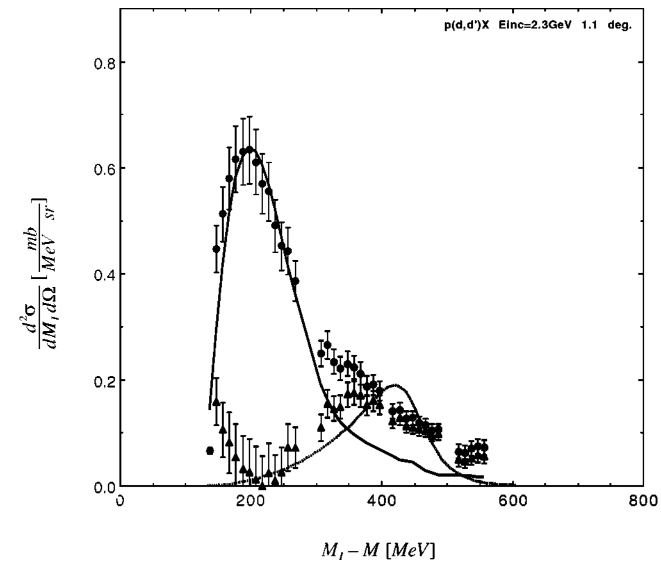

FIG. 4. The double differential cross section $d^2\sigma/dM_I d\Omega$ is shown as a function of excitation energy of the proton. The M_I is the invariant mass of the target system. Solid circles indicate the experimental data obtained in Ref. [20]. The solid line indicates the Δ excitation contribution extracted from data obtained in Ref. [21] and normalized to present data at the peak. The Roper contribution calculated by our model and normalized by a factor of 0.85 is shown by dotted line. Solid triangles are Roper contribution extracted from the data by subtracting the Δ contribution shown by the solid line and the calculated interference contribution with a normalization factor of 0.85.

this excess of cross section to be due to the excitation of the Roper resonance. The calculation again overpredicts the measured cross section in this region.

In order to extract the excitation of the Roper in the 200 to 600 MeV region, we assume that the shape of the calculated DEP is correct and we normalize it to the experimental spectrum at the maximum of the Δ. This leads to an overall normalization factor of 0.85. We then subtract from the measured data the calculated differential cross section for the excitation of the Δ and the interference between Roper excitation and Δ excitation in the projectile, as described in Eq. (5), also multiplied by the same normalization factor 0.85. What is left should mainly correspond to the excitation of the Roper resonance plus some physical continuum. In Fig. 3 we plot the measured data points, the predicted calculations normalized by 0.85 and the excess of cross section left once the DEP and interference contributions are subtracted. The excess of cross section has a maximum around 400 MeV, a width at half maximum of about 230 MeV, and an asymmetric shape with a long low energy tail. The calculation of the Roper contribution, normalized by the factor 0.85, agrees qualitatively in shape and strength with the experimental cross section left once we have subtracted the DEP and the interference. Only the theoretical peak is shifted to higher excitation energy by about 25 MeV. The total experimental excess cross section, up to 540 MeV, is 32 ± 8 mb/sr to be compared to the predicted cross section of 28 mb/sr for the Roper resonance. As mentioned earlier, this experimental cross section should be in principle an upper limit since no underlying continuum corresponding to other physical processes has been subtracted. However, in Ref. [12] other possible mechanisms were studied, and they were found to be small, leaving only the Δ excitation in the projectile and Roper excitation in the target as responsible for the reaction cross section in the energy region studied here. According to this, the signal obtained here for the Roper excitation, within experimental and theoretical uncertainties, should be rather fair.

An empirical way to subtract the DEP contribution was done in Ref. [20], and this is shown in Fig. 4. The shape of the excitation of the Δ in the projectile is taken from the measurements of Baldini *et al.* [21]. The assumption being that at $T_d = 1.6$ GeV, the measured spectrum is mainly dominated by the DEP mechanism and therefore its shape is a good empirical shape for this excitation. This shape is normalized to the data obtained at $T_d = 2.3$ GeV, at the maximum of the Δ resonance. Once this empirical DEP contribution and also the interference contribution evaluated as in the previous case are subtracted, a wide structure is left, centered at 350 MeV with a width at half maximum of 230 MeV. The total cross section in this structure (up to 540 MeV of excitation energy) is of the order of 34 ± 8 mb/sr. This value is in agreement with our previous determination of the excess cross section. The shape of the excess cross section is more symmetric than on the previous case and this is possibly due to the fact that the empirical spectrum taken from Ref. [21] already contains some contribution from the excitation of the Roper.

We have also compared our theoretical results with data

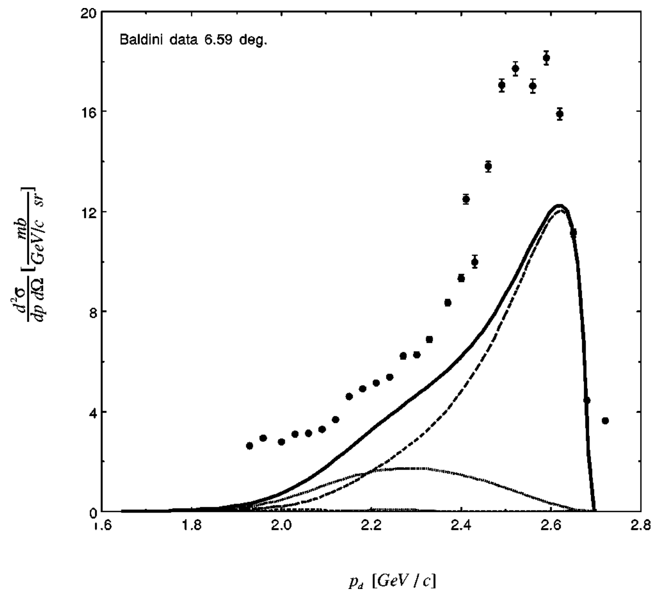

FIG. 5. The double differential cross section $d^2\sigma/dpd\Omega$ is shown as a function of the emitted deuteron momentum at $T_d = 1.6$ GeV. Solid circles indicate the experimental data obtained in Ref. [21]. The theoretical calculations are also shown in the figure, which are total spectrum (solid line), contribution from Δ excitation (dashed line), and contribution from Roper excitation (dotted line).

at 1.6 GeV [21]. The data measured at 6.59° and 8.05° are respectively compared to our predictions in Figs. 5 and 6.

Our calculated results reproduce the overall shape of the spectrum well. However, the theoretical results are about 30% smaller than the data at 6.59° and about 40% at 8.05°.

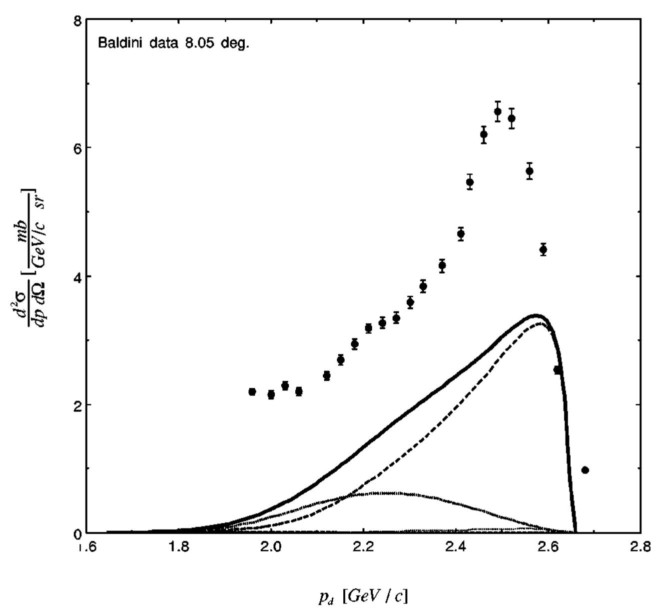

FIG. 6. The double differential cross section $d^2\sigma/dpd\Omega$ is shown as a function of the emitted deuteron momentum at $T_d = 1.6$ GeV. Solid circles indicate the experimental data obtained in Ref. [21]. The theoretical calculations are also shown in the figure, which are total spectrum (solid line), contribution from Δ excitation (dashed line), and contribution from Roper excitation (dotted line).

This discrepancy has to be looked at, however, in the proper perspective. Indeed, the angles where the cross sections are measured in Ref. [21] are $\theta \geqslant 6.6°$. At the smallest angle the cross section has fallen by a factor of 30 from the forward direction. This fall down is mostly due to the deuteron form factor which involves large momentum transfers. In this case our neglect of the d wave in the deuteron is not justified. This, and other approximations could explain these discrepancies. In view of the fact that they represent only about 1% of the integrated cross section, we pay no further attention to these discrepancies, but the qualitative agreement found also gives partial support to the model.

In what follows we would like to make some estimates of the theoretical uncertainties in the present analysis of the data. One of the sources of uncertainty is our neglect of the d wave in the deuteron wave function. The other one is the possible effect of Fermi motion in the deuteron. These two factors could change the shape on the Δ excitation strength and hence lead to uncertainties in the Roper excitation after the DEP strength and interference are subtracted from the data.

We begin by the effect of Fermi motion. The deuteron Fermi motion is considered here in the same way as done in Ref. [9]. It affects the Δ propagator which enters the evaluation of the DEP mechanism. This propagator is given by

$$G_\Delta(s) = \frac{1}{\sqrt{s} - M_\Delta + \frac{i}{2}\Gamma_\Delta(s)}, \tag{9}$$

where the variable s is taken as

$$s = (q^0 + M)^2 - \left(\frac{\vec{q} + \vec{p}_\pi}{2}\right)^2, \tag{10}$$

where q and p_π are the momenta of the exchanged meson, and the emitted pion, respectively, taken in the frame of reference where the deuteron is at rest. In this approximation the momentum transfer is shared equally by the initial and final nucleon in the deuteron. The fairness of this approximation to account for Fermi motion of the nucleus was well established in Refs. [26,27] in the study of coherent pion photoproduction with similar momentum transfers as here. However, in order to see the effects of Fermi motion and have a feeling for possible uncertainties from this source we have conducted new calculations in which in Eq. (10) we assume the initial momentum of the struck nucleon of the deuteron to be zero. This replaces $(\vec{q} + \vec{p}_\pi)/2$ in that equation by $\vec{q}$.

We can see the results of the new calculation in Fig. 7. We can see that the strength of the Δ excitation is increased by about 20%. The prescription followed here to account for Fermi motion was found in Refs. [26,27] to be rather accurate, but even then we see that the effects of ignoring it altogether do not bring drastic changes in the cross section. The possible uncertainties from this source are further minimized if we normalize the theoretical results to the experimental cross section, as we have done in the analysis of this

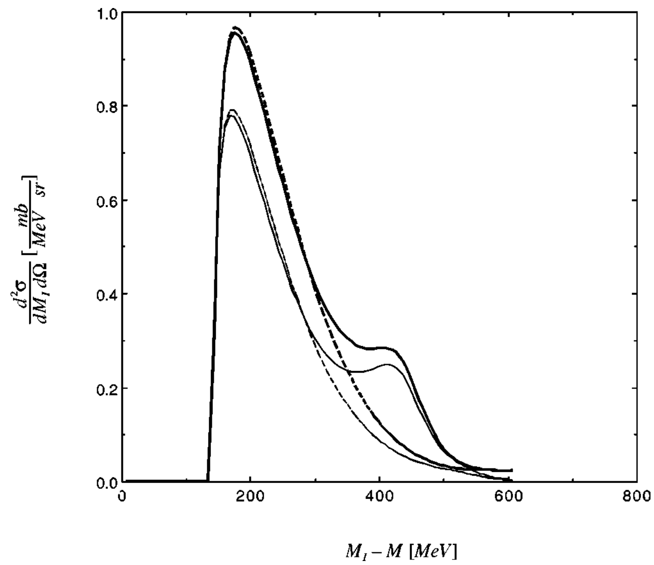

FIG. 7. The double differential cross section $d^2\sigma/dM_I d\Omega$ is shown as a function of excitation energy of the proton. The M_I is the invariant mass of the target system. Calculated total spectrum (solid line) and Δ excitation contribution (dashed line) are shown. Thin lines are the same results as shown in Fig. 2. Thick lines indicate the results obtained neglecting the Fermi motion of nucleon in the projectile, see text.

work. Indeed, if we do so we obtain the results shown in Fig. 8, which are shown superposed to those of Fig. 3. As we can see there, the differences found between neglecting the Fermi motion, or taking it according to our prescription, are very small up to 500 MeV of excitation energy, once the normalization of the cross section around the peak of the delta resonance is done.

As for the d wave of the deuteron we have proceeded as follows: In the evaluation of the deuteron form factor of Eq.

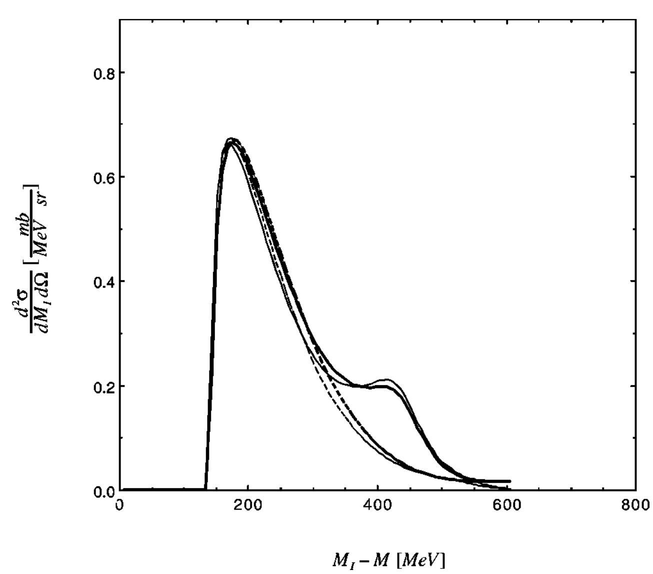

FIG. 8. Same as Fig. 7 except for the normalization to the experimental strength. Thin lines correspond to the calculated results in Fig. 3.

(6) we have taken only the s wave of the deuteron so far. Inclusion of the d wave into our scheme would lead to two parts. One with the same structure as we have, which goes with the $j_0(kr/2)$ component of the exponential, but substituting u^2 by u^2+w^2 in Eq. (6) (u and w are the s- and d-wave parts of the deuteron wave function, respectively), and another one which goes with the $j_2(kr/2)$ component of the exponential. Detailed evaluations of these two parts in the deuteron form factor can be seen in Ref. [28] and there we see that up to 500 MeV/c the j_2 part of the form factor contributes less than 10%. On the other hand the difference between the j_0 component evaluated with just the s-wave (normalized to unity) on the s plus d-wave parts of the deuteron wave function are smaller than 4% up to this momentum. In our case 500 MeV/c momentum transfer corresponds to an excitation energy of around 550 MeV in Fig. 2, just the tail of the distribution beyond the Roper excitation region which we have studied here. On the other hand in the case of Fig. 5, 500 MeV/c would appear at p_d around 2.25 GeV/c and in Fig. 6 one has already 500 MeV/c momentum transfer around the peak of the distribution. Hence, our neglect of the d-wave part of the wave function would induce more uncertainties, in the line we discussed above when we discussed the Baldini's data.

Altogether, we can safely say that in our analysis of the Roper excitation the uncertainties coming from the theoretical model and approximations done are at the level of 10–15 %.

IV. CONCLUSION

With the help of a theoretical model previously used to analyze the (α,α') reaction on the proton, exciting the Δ in the projectile plus the Roper, we have analyzed data on the (d,d') reaction on proton targets at a deuteron energy 2.3 GeV. The use of the model becomes necessary because there is an important interference between the mechanism of delta excitation in the projectile and Roper excitation in the target (followed by πN decay). We observed that the model gave a good reproduction of the shape of the Δ excitation in the target, but the normalization exceeded the data by about 20%. In view of that in order to subtract this contribution and obtain the strength for Roper excitation, we found it justified to normalize the theoretical results by a factor 0.85 which leads to good agreement with the data in the Δ excitation region. Similarly we multiplied by the same factor the interference term, calculated theoretically, and these two pieces of ''background'' were subtracted from the measured data in order to obtain the Roper excitation strength. We found a qualitative agreement with the theoretical predictions for Roper excitation of the model, also normalized by the same factor.

In order to estimate uncertainties due to the use of a theoretical model in the analysis we compared our results to those obtained in Ref. [20], where an empirical approach was used to subtract the DEP contribution using the shape of the Δ resonance excitation from a previous measurement at the lower energies, where there should be a small contribution of Roper excitation. The results obtained with both methods agree qualitatively, the integrated strengths obtained are similar, only the peaks of the Roper strength appear a bit shifted with respect to each other in the two analyses. We estimate that considering statistical and systematic errors, the latter ones from the model dependence of the subtractions, the strength of the Roper determined here is accurate within 25%, and within these errors the agreement with theory can be claimed acceptable. The shape and the width of the Roper strength are compatible with the empirical information about the resonance.

The present analysis confirms the substantial strength for $NN \rightarrow NN^*$ transition in the scalar channel which has been shown already to have important repercussions in different physical phenomena at intermediate energies. These results, and the importance that the isoscalar excitation of the Roper is bound to have in other processes, should stimulate further experiments at higher energies.

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