Nuclear Physics A, 580, 4, 577-594. DOI:10.1016/0375-9474(94)90782-X

QUARK EFFECTS, MESON EXCHANGE CURRENTS AND BACKGROUND IN THE $d(e,e'p)\Delta$ REACTION

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Abstract

We have studied in detail the cross sections for the $d(e,e'p)\Delta$ leading to the emission of a fast nucleon and a Δ at rest, which has been advocated as a tool to investigate quark effects in nuclei. We find that ordinary meson exchange currents mechanisms dominate the quark exchange effects in the region of excitation of the Δ and could be competitive at higher energies. Furthermore, at these higher energies, the small cross sections for the quark signal, together with the presence of a background about one order of magnitude bigger than the quark signal, make in any case the extraction of information about quark exchange currents effects extraordinarily difficult.

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1 Introduction

Recent studies of the baryon-baryon components in the deuteron wave function, from the point of view of the quark substructure of the nucleons and nucleon resonances [1, 2, 3], indicated that the amount of preexisting $\Delta\Delta$ components in the deuteron is fairly larger than estimates based on meson exchange between the nucleons and deltas [4]. The possibility of observing these virtual delta components in some reaction where real deltas would be produced raised expectations that such reactions could show evidence of quark exchange effects in nuclei. Concretely the reaction $d(e,e'p)\Delta$ with a fast emerging proton ($T_p \geq 1GeV$, with T_p the proton kinetic energy) and a Δ at rest was suggested in [3], with hopes that the process would be "the first example in nuclear physics where we can see in leading order the quark exchange currents (QEC, i.e. the six-quark structure)". Some preliminary results by Yu. L. Dorodnykh, quoted in [1], indicated that ordinary meson exchange currents would be negligible, thus leaving free way to the interpretation of the data as genuine quark effects.

The purpose of this paper is to make a thorough analysis of the process by studying the cross sections which one expects due to the quark exchange preexisting $\Delta\Delta$ components, those due to competing mechanisms with ordinary meson exchange currents, as well as the background which one would encounter in the implementation of the experiment.

A result of our calculation is that, in a broad region of energies where the experiment was suggested, the cross sections due to the QEC are smaller than 15 % of the background. We have also evaluated the effect of meson exchange currents, MEC, with mechanisms of real Δ excitation, which turn out to be far more efficient than those considered by Dorodnykh and quoted in [1]. In the region of dominance of the MEC mechanisms considered, the cross sections due to these competing mechanisms are larger than those due to quark exchange. At higher energies rough estimates hint at an equilibrium between MEC and QEC, but the extremely small cross sections, the relative large background and uncertainties in the determination of the MEC and QEC make the extraction of information about genuine quark effects far more

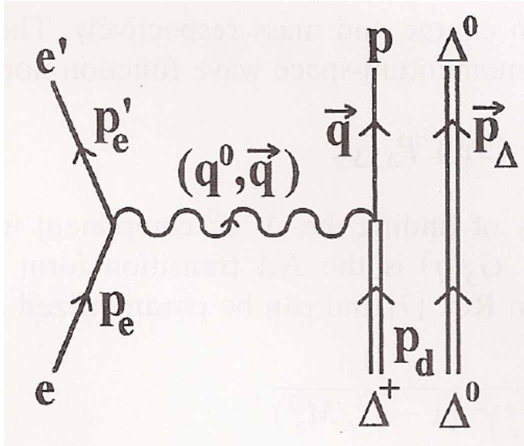

Figure 1: Feynman diagram for the QEC mechanism of the $d(e,e'p)\Delta$ reaction.

difficult than anticipated.

2 Cross section for the $d(e,e'p)\Delta$ reaction from QEC.

In [3] the $\Delta\Delta$ wave function due to QEC was evaluated and the mechanism suggested for the $d(e,e'p)\Delta$ reaction is depicted in fig. 1. One starts from a preexisting off shell $\Delta^+\Delta^0$ component, the Δ^+ is deexcited into a nucleon, which carries all the momentum of the virtual photon, and the Δ^0 acts as a spectator, only that it gets energy to become a Δ^0 with zero momentum and an energy $E_\Delta \approx M_\Delta$. In order to accomplish this the virtual photon has to carry an energy in the deuteron rest frame (neglecting the d binding energy)

$$q^0 = E_N(\vec{q}) + E_\Delta - M_d \tag{1}$$

with E_N, E_Δ the total energy of the fast proton and the delta respectively and M_d the deuteron mass. We follow the steps of [3] and make use of the impulse approximation in order to evaluate the cross section for this process.

The $\gamma N\Delta$ coupling is given by [5]

$$-i\delta\tilde{H}^\mu_{\gamma N\Delta} = -\frac{f_\gamma}{\mu}\sqrt{\frac{2}{3}}\frac{\sqrt{s}}{M_\Delta}\left\{\begin{array}{ll} \frac{\vec{p}_\Delta}{\sqrt{s}} & (\vec{S}^\dagger \times \vec{q}) \\ \frac{p^0_\Delta}{\sqrt{s}} & \left[\vec{S}^\dagger \times (\vec{q} - \frac{q^0}{p^0_\Delta}\vec{p}_\Delta)\right] \end{array}\right\}^\mu + h.c. \tag{2}$$

where $f_\gamma = 0.116$, μ the pions mass, $(p^0_\Delta, \vec{p}_\Delta)$ the fourmomentum of the Δ and $\sqrt{s}$ is the Δ invariant mass $(p^{02}_\Delta - \vec{p}^{\,2}_\Delta)^{1/2}$ and $\vec{S}$ the spin transition operator. The isospin factor $\sqrt{2/3}$ is explicitly incorporated.

In the present case $\vec{p}_{\Delta^+} = 0$ and we get

$$-i\delta\tilde{H}^\mu_{\gamma N\Delta} = -\frac{f_\gamma}{\mu}\sqrt{\frac{2}{3}}\frac{M}{M_\Delta}\left\{\begin{array}{c} 0 \\ \vec{S}^\dagger \times \vec{q} \end{array}\right\}^\mu + h.c. \tag{3}$$

The cross section for the process in Mandl and Shaw normalization [6] is given by

$$\sigma = \frac{1}{v_{rel}}\int\frac{d^3p'_e}{(2\pi)^3}\int\frac{d^3p_N}{(2\pi)^3}\int\frac{d^3p_\Delta}{(2\pi)^3}\frac{m}{E(p'_e)}\frac{m}{E(p_e)}$$

$$\frac{M_d}{E_d}\frac{M}{E(\vec{p}_N)}\frac{M_\Delta}{E(\vec{p}_\Delta)}(2\pi)^4\delta^4(p_e + p_d - p'_e - p_N - p_\Delta)$$

$$L^{\mu\nu}\, W_{\mu\nu}\frac{e^2}{q^4}\left|\tilde{\varphi}_{\Delta^+\Delta^0}(\frac{\vec{p}_N - \vec{p}_\Delta - \vec{q}}{2})\right|^2 |G_\Delta(q)|^2 \tag{4}$$

where $L^{\mu\nu}$ is the leptonic tensor

$$L^{\mu\nu} = \frac{1}{2m^2}\left\{p^\mu_e p'^{\,\nu}_e + p'^{\,\mu}_e p^\nu_e + \frac{1}{2}g^{\mu\nu}q^2\right\} \tag{5}$$

$W_{\mu\gamma}$ is the hadronic tensor, resulting from summing and averaging over spins the current in eq. (2) times its complex conjugate ($\mu\nu$, only spatial indices)

$$W_{\mu\nu} = \frac{2}{9}\left(\frac{f_\gamma}{\mu}\right)^2(\delta_{\mu\nu}\vec{q}^{\,2} - q_\mu q_\nu)\left(\frac{M}{M_\Delta}\right)^2 \tag{6}$$

and e, m the electron charge and mass respectively. The $\Delta\Delta$ deuteron wave function in eq. (4) is the momentum space wave function normalized such that

$$\int d^3k|\tilde{\varphi}_{\Delta^+\Delta^0}(\vec{k})|^2 = (2\pi)^3 P_{\Delta^+\Delta^0} \tag{7}$$

with $P_{\Delta^+\Delta^0}$ the probability of finding the $\Delta^+\Delta^0$ component in the d ground state ($\approx 1.5\%$ in [3]) and $G_\Delta(q)$ is the $N\Delta$ transition form factor, which in the region we move is given in [7] and can be parametrized as

$$G_\Delta(q) = \frac{1}{(1 - q^2/M_v^2)^2}\frac{1}{(1 - q^2/M_a^2)} \tag{8}$$

with $M_v^2 = 0.71\,GeV^2$, $M_a^2 = 4\,GeV^2$.

The kinematics suggested in [3] is such that $\vec{p}_N = \vec{q}$, $\vec{p}_\Delta = 0$ and hence the argument of the $\Delta\Delta$ deuteron wave function component is zero, hence maximizing the quark exchange effects. The $\vec{p}_\Delta$ integration can be used to eliminate the δ^3 of three momentum and, given the fact that the Δ produced is an unstable particle, the remaining δ^0 of energy must be written as

$$\delta(E_e + E_d - E'_e - E_N - E_\Delta) \rightarrow -\frac{1}{\pi} Im \frac{1}{E_e + E_d - E'_e - E_N - E_\Delta + i\frac{\Gamma}{2}(s)} \tag{9}$$

where $\Gamma(s)$ is the width of the outgoing Δ as a function of its invariant mass $\sqrt{s}$ and

$$\Gamma = \frac{2}{3}\frac{1}{4\pi}\frac{f^{*2}}{\mu^2}\frac{M}{\sqrt{s}} p_{CM}^3 \quad , \quad p_{CM} = \frac{\lambda^{1/2}(s, M^2, \mu^2)}{2\sqrt{s}} \tag{10}$$

with $\lambda(.)$ the Kallen function.

Thus we can write the differential cross section for the process as

$$\frac{d\sigma}{dE'_e d\Omega'_e dE_N d\Omega_N} = \frac{E_e}{E'_e}\frac{p_N M M_\Delta}{E_\Delta}\frac{1}{(2\pi)^5}\frac{1}{9}\frac{f_\gamma^2}{\mu^2}\frac{e^2}{q^4}$$

$$|\tilde{\varphi}_{\Delta\Delta}(0)|^2 |G_\Delta(q)|^2 [2\vec{p}_e^{\,2}\vec{q}^{\,2} - 2(\vec{p}_e\cdot\vec{q})^2 - \vec{q}^{\,2} q^2] \left(\frac{M}{M_\Delta}\right)^2$$

$$\frac{1}{\pi}\frac{\Gamma(s)/2}{(E_e + E_d - E'_e - E_N - E_\Delta)^2 + (\Gamma(s)/2)^2} \tag{11}$$

From ref. [3], (middle curve of fig. 5), we obtain:

$$|\varphi_{\Delta^+\Delta^0}(0)|^2 = 6.71 \times 10^{-2}\, fm^3 \tag{12}$$

with the normalization of eq. (7), which differs from the one in ref. [3] in a factor $(2\pi)^3/4\pi$.

3 Limitation in the impulse approximation.

The spirit of the impulse approximation (IA) is that the elementary process occurs in just one baryon (one Δ in the present case), the other baryon acting just as a spectator. If the spectator baryon is forced to leave with a momentum

$\vec{p}_s$, this momentum is provided by the momentum distribution of the deuteron wave function.

However, there is no provision in this approximation to transfer energy, and in the present case one is forced to transfer an energy $E_\Delta - M$ to the spectator Δ. Technically one can see the approximation in eq. (4) where the dynamics is considered in one Δ, but the δ of conservation of four momentum is applied to the whole system. One pays a price in doing that and one observes that the cross section is not Lorentz invariant since the argument of the deuteron wave function $(\vec{p}_N - \vec{p}_\Delta - \vec{q})/2$ is not invariant. This argument changes from one frame to another, particularly in the case when a large energy transfer has been enforced.

We can get a feeling of the accuracy of the approximation in the present case by changing from de d laboratory frame to the γd center of mass frame. We get

$$\frac{\vec{p}_{N^{CM}} - \vec{p}_{\Delta^{CM}} - \vec{q}_{CM}}{2} = \frac{v}{2\sqrt{1-v^2}}(q^0 + E_\Delta - E_N(q)) \tag{13}$$

with

$$v = \frac{q}{M_d + q^0} \tag{14}$$

This CM argument is $185\, MeV/c$ at $T_p = 1\, GeV$ and $262\, MeV/c$ at $T_p = 2\, GeV$ for $E_\Delta = M_\Delta$. While such large arguments involving the NN components would make the IA unreliable, when applied to the $\Delta\Delta$ components do not induce dramatic changes, because the $\Delta\Delta$ wave function in momentum space stretches over a large range of momenta (reciprocally, it is very confined in coordinate space). By looking at the $\Delta\Delta$ wave function in [3], $|\tilde{\varphi}_{\Delta\Delta}|^2$ would be reduced by 23% at $T_p = 1\, GeV$ and by 35 % at $T_p = 2\, GeV$. Since in any frame of reference $|\tilde{\varphi}_{\Delta\Delta}|^2$ will be smaller than in the lab frame, one could conclude that the values we obtain for the QEC are an overestimate of more realistic results but not by a large amount. Later on we shall comment on other uncertainties tied to the static character of the approximation (i.e. lack of retardation effects).

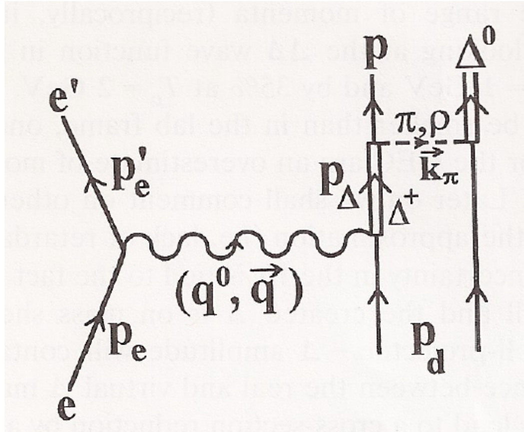

Figure 2: Feynman diagram for the MEC mechanism of the $d(e, e'p)\Delta$ reactions driven by Δ excitation.

Another source of uncertainty in the IA is tied to the fact that the Δ constituent is far off its mass shell and the created Δ is on mass shell. Consequently, the elementary half off shell projectile $-\Delta$ amplitude will contain a form factor depending on the difference between the real and virtual Δ masses. According to ref. [4, pag. 320] this could easily lead to a cross section reduction by an order of magnitude, though there are not reliable estimates about it.

4 Meson exchange currents.

The meson exchange currents allow us to produce ΔN components from the NN components of the nucleons through the exchange of mesons. One useful approach to the MEC is to start from a model for the $\gamma N \to \pi N$ process and then attach the π to the second nucleon in the deuteron. This is the procedure followed in [8] to study real photon absorption in nuclei up to the energy of excitation of the Δ resonance. We have checked that in the present case, as well as in [8], the dominant mechanism around the Δ excitation region is given by the diagram of fig. 2. We have considered pion and ρ-meson exchange in fig.2.

The ingredients needed are the $\pi N\Delta$ and $\rho N\Delta$ vertices

$$-i\delta\tilde{H}_{\pi N\Delta} = \frac{f^*}{\mu}\vec{S}\cdot(\vec{k}_\pi - \frac{k^0_\pi}{\sqrt{s}}\vec{p}_\Delta)T^\lambda + h.c.$$

$$-i\delta\tilde{H}^i_{\rho N\Delta} = \sqrt{C_\rho}\frac{f^*}{\mu}\left[\vec{S}\times(\vec{k}_\pi - \frac{k^0_\pi}{\sqrt{s}}\vec{p}_\Delta)\right]^i T^\lambda + h.c. \qquad (15)$$

where T^λ is the isospin transition operator, $f^* = 2.12$ and $C_\rho = 3.96$ [9]. For on shell pions, $\vec{k}_\pi - \frac{k^0_\pi}{\sqrt{s}}\vec{p}_\Delta$ is the pion momentum in the Δ CM frame (next order relativistic corrections to eq. (15) needed to provide this pion CM are already small, of the order of 5 %, but we include them also in our results).

The cross section for the process of fig. 2 is given by eq. (4) substituting

$$W_{\mu\nu}|\tilde{\varphi}_{\Delta^+\Delta^0}(0)|^2 \rightarrow W^{MEC}_{\mu\nu}$$

$$W^{MEC}_{\mu\nu} = \overline{\sum_{s_d}}\sum_{s_N s_\Delta} < s_N s_\Delta|j_\mu|s_d > < s_d|j^\dagger_\nu|s_N s_\Delta >$$

with

$$j^\mu = j^\mu_\pi + j^\mu_\rho$$

and

$$\vec{j}^{\,\pi} = -\sqrt{\frac{2}{27}}\frac{f_\gamma}{\mu}\left(\frac{f^*}{\mu}\right)^2\frac{M}{M_\Delta}\int\frac{d^3k_\pi}{(2\pi)^3}\frac{1}{k^{02}_\pi - \vec{k}_\pi^{\,2} - \mu^2 + i\varepsilon}S_\Delta(p_\Delta)$$

$$\vec{S}_1\cdot(\vec{k}_\pi - \frac{k^0_\pi}{\sqrt{s}}\vec{p}_\Delta)\vec{S}_1^{\,\dagger}\times\vec{q}\,\vec{S}_2^{\,\dagger}\cdot\vec{k}_\pi\,\tilde{\varphi}_{NN}(\vec{k}_\pi)\,F^2_\pi(k_\pi) \qquad (16)$$

where $S_\Delta(p_\Delta)$ is the Δ propagator [14],

$$S_\Delta(p_\Delta) = \frac{1}{\sqrt{s} - M_\Delta + i\frac{\Gamma(s)}{2}} \qquad (17)$$

$F(k_\pi)$ the $\pi N\Delta$ form factor, $\vec{S}_1, \vec{S}_2$ are the transition spin operators from 1/2 to 3/2 [14] for the particle 1 and 2 respectively, and $\tilde{\varphi}_{NN}(\vec{k}_\pi)$ is the deuteron wave function in momentum space, which we take from the Paris potential [10]. We consider only the s-wave of the deuteron wave function.

For the ρ component of the current we have to substitute

$$\frac{k_\pi^i k_\pi^j}{k_\pi^{02} - \vec{k}_\pi^2 - \mu^2 + i\varepsilon} \tag{18}$$

by

$$\frac{\sqrt{C_\rho}(\delta^{ij}\vec{k}_\pi^{\ 2} - k_\pi^i k_\pi^j)}{k_\pi^{02} - \vec{k}_\pi^{\ 2} - m_\rho^2 + i\omega_\rho \Gamma_\rho(s_\rho)} \tag{19}$$

with m_ρ the ρ mass, $\omega_\rho = (m_\rho^2 + \vec{k}_\pi^{\,2})^{1/2}$, $\Gamma_\rho(s_\rho)$ the ρ width [14] and $F_\pi(k_\pi)$ is substituted by $F_\rho(k_\pi)$.

The π, ρ form factors are taken of the monopole type as in [8] with $\Lambda_\pi =$ 1300 MeV and $\Lambda_\rho = 1400$ MeV.

In eq. (16) the coefficient $\sqrt{2/27}$ accounts for isospin factors and the fact that we can couple the photon to either of the nucleons in the deuteron. We neglect a small j^0 component of the order of $k_\pi/(M + q^0)$ with respect to the spatial components.

We are interested on comparing the QEC and MEC effects. For this purpose we evaluate the ratio between the cross sections for both processes (4), (16), which is given by

$$\frac{d\sigma_{MEC}}{d\sigma_{QEC}} = \frac{46}{243}\left(\frac{f^*}{\mu}\right)^4 |S_\Delta(p_\Delta)|^2 \frac{|I|^2}{|\tilde{\varphi}_{\Delta^+\Delta^0}(0)|^2} \tag{20}$$

where

$$I = \frac{1}{3}\int \frac{d^3k_\pi}{(2\pi)^3}\tilde{\varphi}_{NN}(\vec{k}_\pi)\frac{\vec{k}_\pi^2}{k_\pi^{0\,2} - \vec{k}_\pi^{\ 2} - \mu^2 + i\varepsilon}F_\pi^2(k_\pi) +$$

$$+\frac{2}{3}C_\rho \int \frac{d^3k_\pi}{(2\pi)^3}\tilde{\varphi}_{NN}(\vec{k}_\pi)\frac{\vec{k}_\pi^{\ 2}}{k_\pi^{0\,2} - \vec{k}_\pi^{\,2} - m_\rho^2 + i\omega_\rho\Gamma_\rho(s_\rho)}F_\rho^2(k_\pi) \tag{21}$$

We can observe a constructive interference between π and ρ exchange, since only the scalar part of the meson exchange contributes and it has the same sign for both mesons. The ρ contribution is about 16% of the total.

An important feature to note is that because the exchanged pion carries an energy bigger than the pion mass it can originate poles by picking up the appropriate momentum components from the deuteron wave function.

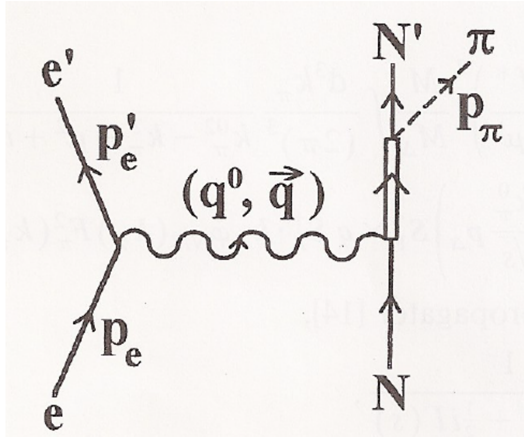

Figure 3: Diagramatic representation for pion electroproduction on the nucleon in the Δ excitation region.

The contribution from the on shell pion in the MEC has an easy physical interpretation as a two step process, the first one for $(e, e'\pi)$ on one nucleon, followed by π recombination with the second nucleon to give a Δ. Recalling general features of pion multiple scattering on the deuteron [11] we would expect this two step process to provide a smaller cross section than ordinary $(e, e'\pi)$ on the deuteron (of the order of 10%) as it will turn out to be the case. This also tells us about the range of validity of our MEC contribution, which is confined to the region where the Δ excitation mechanism for $(e, e'\pi)$ on the nucleon, given by the diagram of fig. 3, gives an accurate description of the $(e, e'\pi)$ on the nucleon. We address this question in the next section.

The energy transfer also has a repercussion on the real part of the pionic MEC contribution, (i.e., the contribution from the off shell pion, or equivalently the contribution coming from the principal part of the $\vec{k}_\pi$ integration). This contribution is tremendously enhanced by the existence of the energy transfer. As an example to show the relevance of a proper consideration of the energy exchange we have done a "static" calculation by setting the pion energy $k_\pi^0 = 0$. The resulting cross sections is smaller than the accurate, non static one, by about a factor 350. This is very important to note and raises a warning about the use of static pictures in processes of this type. For instance, the ordinary static evaluation of the amount of preexisting $\Delta's$ in the deuteron is obtained with a diagram like in fig. 4a where no energy is transfered by the

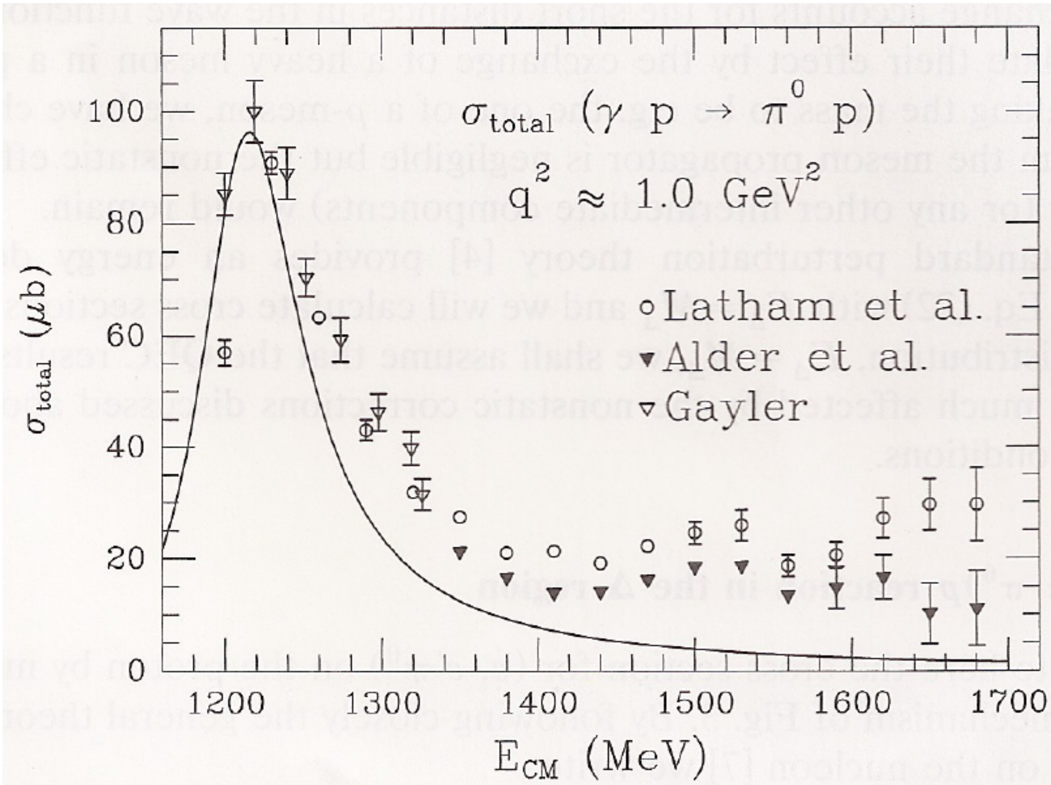

Figure 4: Experimental data and theoretical results with the Δ excitation model for the $\gamma_v p \to \pi^0 p$ cross section at $q^2 = 1.0\ GeV^2$ as a function of the $\gamma_v p$ energy in the CM frame, E_{CM}. Experimental data from refs. [15, 16, 17].

pion [4]. If we evaluate the contribution of fig. 4b to the present process with $k^0_\pi = 0$ or the required k^0_π, the results differ by about two order of magnitude. The differences come from two sources. On one hand the use of the non static pion propagator increases the cross section by about a factor 350, as we noted. On the other hand the Δ propagator in the non static case is given by

$$S_\Delta \simeq \frac{1}{M - E_\Delta + M - M_\Delta} = \frac{1}{2M - (E_\Delta + M_\Delta)} \tag{22}$$

which depends upon the value of E_Δ. This factor changes as we vary the kinematic conditions in order to obtain the Δ shape in the $d(e,e'p)\Delta$ cross section. A static picture also misses this energy variation in the Δ propagator. If we set $k^0_\pi \equiv E_\Delta - M = 0$ in our example of "static" calculation, S_Δ is about 1/2 of S_Δ non static for $E_\Delta \simeq M_\Delta$. The combined effect of these two retardation effects has as a consequence the increase of the cross section by about two orders of magnitude, as we quoted.

One may wander what would happen to the QEC if retardation effects were taken into account. Since a proper evaluation for the present conditions is not available one can not provide a precise answer, but hints can be given. In as much as the quark exchange accounts for the short distances in the wave function, we could roughly simulate their effect by the exchange of a heavy meson in a picture like fig. 4b. By taking the mass to be f.i. the one of a ρ-meson we have checked that the effect from the meson propagator is negligible but the non static effects on the Δ propagator (or any other intermediate components) would remain.

Since a standard perturbation theory [4] provides an energy denominator equivalent to eq. (22) with $E_\Delta = M_\Delta$ and we will calculate cross sections only at the peak of the distribution, $E_\Delta = M_\Delta$, we shall assume that the QEC results of [3] would not be much affected by the non static corrections discussed above in these kinematical conditions.

5 The $p(e, e'\pi^0)p$ reaction in the Δ region.

We evaluate here the cross section for $(e, e'\pi^0)$ on the proton by means of the Δ excitation mechanism of fig. 3. By following closely the general theory of the $(e, e'\pi)$ reaction on the nucleon [7] we write

$$\frac{d\sigma}{d\Omega'_e dE'_e d\Omega^*_\pi} = \Gamma \, \frac{d\sigma_T}{d\Omega^*_v} \tag{23}$$

where

$$\Gamma = \frac{\alpha}{2\pi^2} \, \frac{1}{-q^2} \, \frac{p'_e}{p_e} \, \frac{1}{1-\epsilon} k_\gamma$$

$$k_\gamma = \frac{s - M^2}{2M}; \quad \epsilon = \left[1 - \frac{2\vec{q}^{\,2}}{q^2} tg^2 \frac{\theta}{2}\right]^{-1}$$

and $d\sigma_T/d\Omega^*_v$ is the transverse cross section for virtual photons in the πN CM frame, given by

$$\frac{d\sigma}{d\Omega^*_v} = \frac{\alpha}{4\pi} \frac{p_\pi}{k_\gamma} \frac{M}{\sqrt{s}} \overline{\sum_{s_N}} \sum_{s_{N'}} |t|^2$$

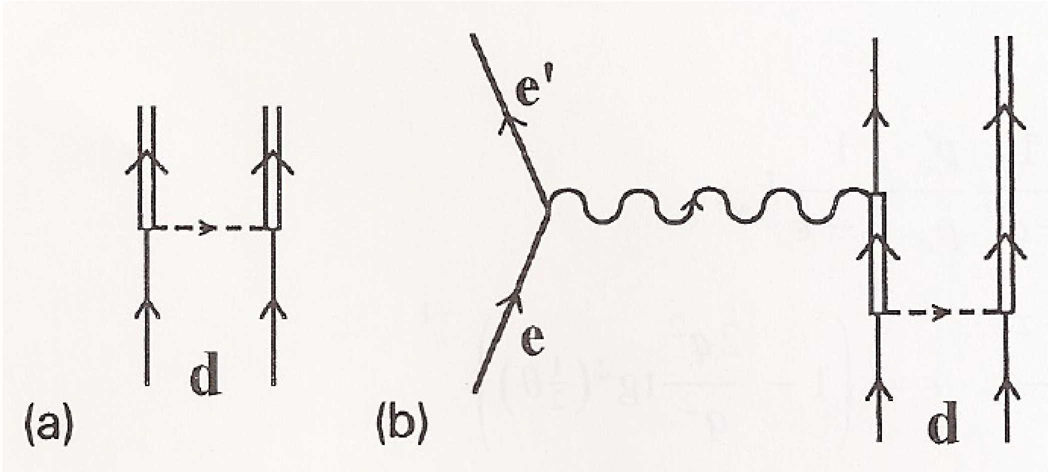

Figure 5: a) Mechanism to generate preexisting $\Delta's$ in the deuteron wave function with pion exchange. b) Mechanism for the $d(e,e'p)\Delta$ reaction based on the preexisting $\Delta's$ of diagram 5a).

and the t matrix is easily evaluated by taking into account the $\pi N\Delta$ and $\gamma N\Delta$ vertices of eqs. (2) and (15). After integrating over the pion angle we obtain the integrated $\gamma_v p \to \pi^0 p$ cross section which is given by

$$\sigma(\gamma_v \to \pi^0 p) = 2\left(\frac{2}{9}\right)^2 \left(\frac{f^*}{\mu}\right)^2 \left(\frac{f_\gamma}{\mu}\right)^2 \frac{1}{4\pi}\frac{p_\pi}{k_\gamma}$$

$$\frac{M}{\sqrt{s}}\vec{p}_\pi{}^2 \vec{q}^2 \left| \frac{1}{\sqrt{s} - M_\Delta + i\frac{\Gamma(s)}{2}} \right|^2 |G_\Delta(q)|^2 \tag{24}$$

where $\vec{p}_\pi$ and $\vec{q}$ are written in the πN CM frame.

In fig. 5 we compare the results with our model to the experimental results for $q^2 = -1\, GeV^2$ as a function of $\sqrt{s}$. We observe that the model reproduces fairly well the peak of the Δ distribution and the slope down at higher energies, but at $\sqrt{s} = 1300\, MeV$ it already underestimates the cross section by nearly a factor of two. At higher energy $\sqrt{s} \simeq 1400 - 1600\, MeV$ the model clearly undepredicts the data indicating the relevance of other mechanisms and contribution from other resonances. It is well known that in this region one can not isolate energies where one or another resonance are dominant, but all of them up to $M_R \simeq 1900\, MeV$ must be considered and they interfere strongly [12, 13] . As an example 10 resonances are considered in [12].

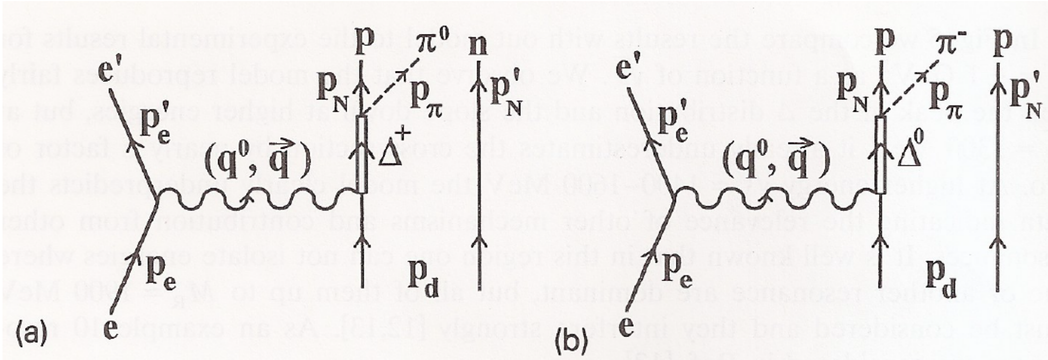

Figure 6: Mechanism for the background that one meets in the $d(e,e'p)\Delta$ reaction. a) with $\pi^0 n$ production, b) with $\pi^- p$ production.

6 Background for the $d(e,e'p)\Delta$ reaction.

Figs. 1 and 2 are idealization of the process. In practice the Δ will decay into a pion and a nucleon, and for a Δ at rest and $E_\Delta = M_\Delta$ the π and the nucleon will go back to back with a momentum $p = 227\,MeV/c$. An eventual experimental searching for this Δ production would see the correlated πN pairs coming from Δ decay on top of a background of uncorrelated πN pairs with exactly the same kinematics. The presence of a large background makes more difficult the identification of the signals and their knowledge is always important in the planning of experiments.

By sticking to our Δ excitation model we find a source of background in the process $(e,e'\pi)$ on the deuteron with one proton going out fast with momentum $\vec{q}$, the pion going out with a momentum 227 MeV/c in the lab system and the spectator nucleon with the same momentum as the pion but in the opposite direction. This is depicted in figs. 6a and 6b.

The cross section for this process is given by

$$\sigma = \frac{1}{v_{rel}} \int \frac{d^3p'_e}{(2\pi)^3} \int \frac{d^3p_N}{(2\pi)^3} \int \frac{d^3p'_N}{(2\pi)^3} \int \frac{d^3p_\pi}{(2\pi)^3} \frac{1}{2\omega_\pi}$$

$$\frac{m}{E(p_e)} \frac{m}{E(p'_e)} \frac{M_d}{E_d} \frac{M}{E_N} \frac{M}{E'_N} (2\pi)^4 \delta(p_e + p_d - p'_e - p_N - p'_N - p_\pi)$$

$$L^{\mu\nu} W_{\mu\nu} \frac{e^2}{q^4} \left| \tilde{\varphi}_{NN} \left(\frac{\vec{p} + \vec{p}_\pi - \vec{p}'_N - \vec{q}_N}{2} \right) \right|^2 |G_\Delta(q)|^2 \qquad (25)$$

where $\vec{p}_N = \vec{q}$ and $\vec{p}'_N = -\vec{p}_\pi$. Thus one obtains the deuteron wave function in momentum space with argument $\vec{p}_\pi$.

$W_{\mu\nu}$ is given by

$$W_{\mu\nu} = \overline{\sum_{s_d}} \sum_{s_p s_n} < s_p s_n | j_\mu | s_d > < s_d | j_\nu^\dagger | s_p s_n >$$

$$\vec{j} = i \sqrt{\frac{2}{3}} \frac{f^*}{\mu} \frac{f_\gamma}{\mu} \frac{M}{M_\Delta} S_\Delta(p_\Delta) \vec{S}_1 \cdot (\vec{p}_\pi - \frac{p_\pi^0}{\sqrt{s_\Delta}} \vec{p}_\Delta) \vec{S}_1^\dagger \times \vec{q} \tag{26}$$

Once again we are neglecting the small j^0 component and the factor $\sqrt{2/3}$ already accounts for the isospin factors for figs. 6a and 6b, and the possibility of coupling the photon to either of the nucleons in the deuteron.

The ratio between the background cross section and the QEC one at the QEC peak, where $\vec{p}_\Delta = 0$ and $E_\Delta = M_\Delta$, is given by

$$\frac{d\sigma_{BG}}{d\sigma_{QEC}} = \frac{1}{24\pi} \frac{M}{M_\Delta} \left(\frac{f^*}{\mu} \right)^2 \Gamma \, |S_\Delta(p_\Delta)|^2 \left| \frac{\tilde{\varphi}_{NN}(\vec{p}_\pi)}{\tilde{\varphi}_{\Delta\Delta}(0)} \right|^2 (p_\pi^2 + p_\pi^{CM\,2}) p_\pi$$

where Γ is the free Δ decay width, p_π and p_π^{CM} are the modulus of the momentum of the outgoing pion in the LAB frame and in the Δ CM frame respectively.

One may worry again about the IA which has also been used to determine the background, since one of the nucleons in the deuteron has been a spectator. By using the same arguments as in section 3 we observe now that there is a change in the argument of the deuteron wave function by going from the lab to the CM frame. This change is given now by

$$\frac{v}{2\sqrt{1-v^2}} (q^0 + E_N(p_\pi) - q^0 - M) = \frac{v}{2\sqrt{1-v^2}} (E_N(p_\pi) - M)$$

with v given by eq. (14) and $p_\pi = 227 MeV$ (for $E_\Delta = M_\Delta$).

In a broad region from $T_p = 800\, MeV$ to $T_p = 1.4\, GeV$ this shift is less than 10 MeV which makes the IA on the NN component of the deuteron a highly accurate tool to determine the background, ever more when the integration over all the directions of $\vec{p}_\pi$ is done. Note that here only an amount $p_\pi^2/2M \approx$

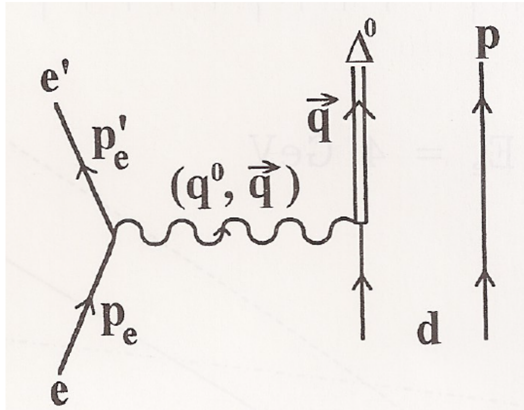

Figure 7: Dominant mechanism for the $d(e, e'p)\Delta$ reaction with a fast Δ and a proton at rest.

27 MeV of energy is transfered to the spectator nucleon, while 293 MeV were transfered in the case of the preexisting $\Delta's$ from section 2.

One should note in this section that if the Δ^0 is produced with momentum $\vec{q}$ in the $d(e, e'p)\Delta$ reaction rather than at rest, the most efficient mechanism is given in fig. 7 and involves the deuteron wave function with zero argument, $\tilde{\varphi}_{NN}(0)$. The ratio of cross sections of this mechanism to the one of the QEC of fig. 1 is $2|\tilde{\varphi}_{NN}(0)/\tilde{\varphi}_{\Delta\Delta}(0)|^2$ which is of the order of 10^5. This means that there is a strong dependence of the cross section on the Δ momentum and good resolution in the determination of the Δ momentum would be needed to avoid extra background in an eventual experiment.

7 Results and discussion.

We have evaluated all the results for an incident electron energy of 4 GeV.

In fig. 8 we see the values of q^0, q needed to create the appropriate kinematical conditions of $\vec{p}_{\Delta^0} = 0$ and $E_{\Delta^0} = M_\Delta$ (the peak of the Δ^0 distribution), together with the value of $\sqrt{s}$ that the Δ^+ has in the MEC mechanism of fig. 2, as a function of T_p. In fig. 9 we show the differential cross section for the QEC and MEC mechanisms. We show the results up to the value of $T_p = 300\, MeV$, or equivalently $\sqrt{s} = 1300\, MeV$, where our model already underestimates the $(e, e'\pi)$ cross section on the nucleon by about a factor of two. From there on the model grossly underpredicts that cross section and hence, as discussed in

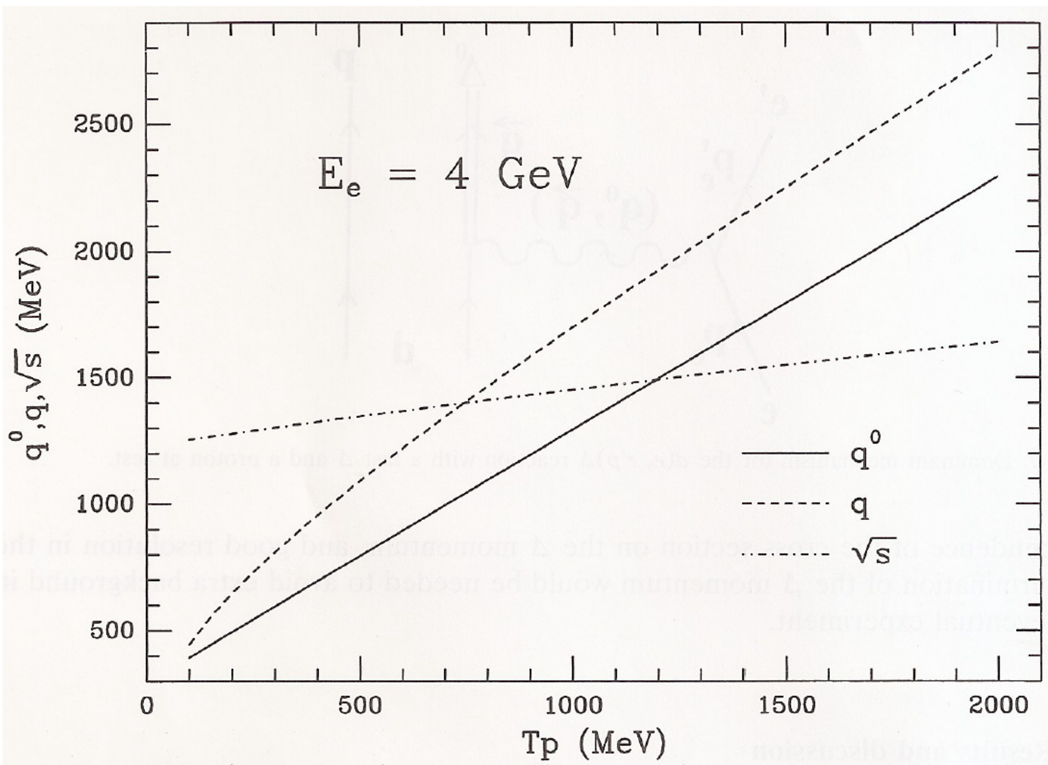

Figure 8: Values of $q^0, q, \sqrt{s}$ as function of T_p for an electron energy of $4\,MeV$, suited to produce the Δ^0 at rest and with energy M_Δ in figs. 1 and 2.

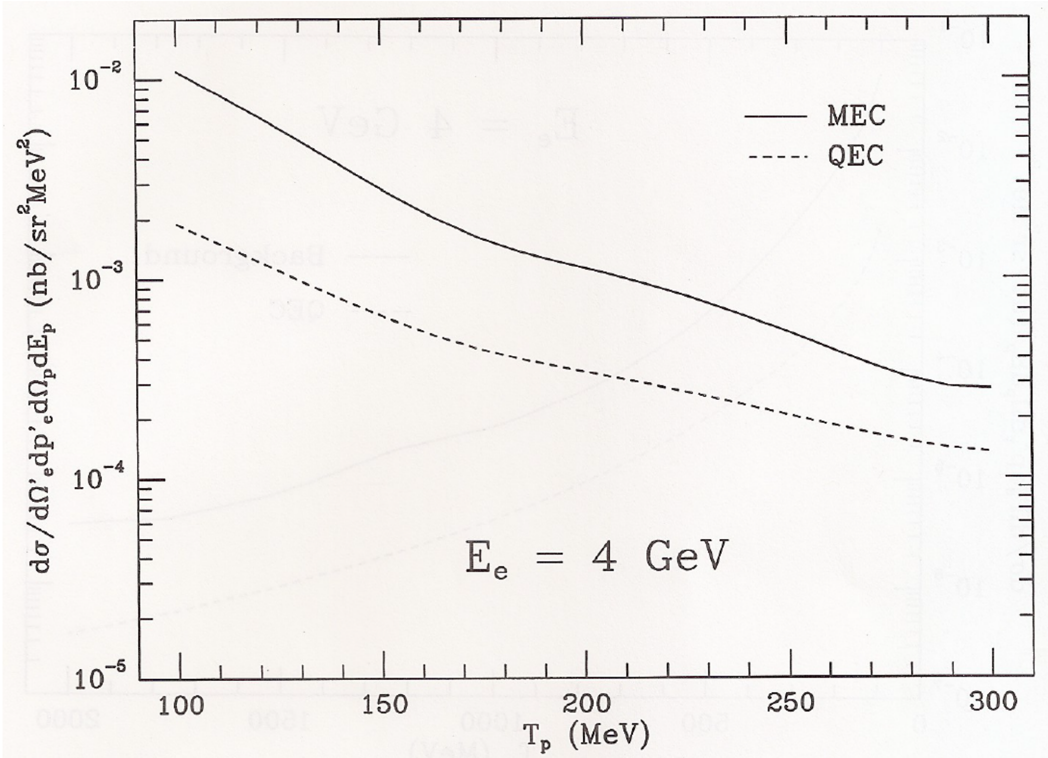

Figure 9: Differential cross sections for the QEC and MEC mechanisms as a function of T_p for $E_e = 4\,GeV$.

a previous chapter, the MEC contribution to the $d(e, e'p)\Delta$ process. It is also worth noting that about half of the contribution comes from the pion on shell, while the other part comes from the off shell pion and the ρ-exchange. What we observe is that the MEC contribution dominates the QEC contribution. Furthermore, one has to accept intrinsic uncertainties in the MEC contribution stemming from the inaccurate knowledge of the deuteron wave function at short distances or off shell extrapolation of the $\pi N\Delta$ vertices. These uncertainties easily change the contribution of the MEC by more than a factor two, which would make the extraction of information about genuine quark effects impossible there.

One can of course ask what would happen if one goes to higher energies as suggested in [3]. Since our model for MEC is no longer accurate one may get a rough idea by scaling the results with the experimental $(e, e'\pi)$ cross section. This is, take the MEC results with the Δ excitation model as a function of energy and multiply them by the ratio of the experimental $\sigma(\gamma_v \to \pi^0 p)$ cross section to the one provided by the Δ excitation model of section 5. While this is a valid procedure for the background, as we shall see, here it can only be taken as a rough estimate. The reason is that a resonance like the $N^*(1520)$ which couples to pions in D-wave would introduce integrals of the type

$$\int k_i k_j k_m \tilde{\varphi}(k) d^3k$$

which vanish in the present case. In practice, because of the recoil terms in the vertices (terms like $\frac{k_\pi^0}{\sqrt{s}}\vec{p}_\Delta$ in eq. (15)) there is a finite contribution from this resonance, but the MEC contribution does not scale like the $(e, e'\pi)$ cross section mediated by the $N(1520)$ excitation, where the non recoil terms also contribute. With this caveat and taking the experimental cross section for $\sigma(\gamma_v)$ from [15] one obtains ratios of MEC to QEC of the order of unity in a broader range of energies up to $\sqrt{s} \simeq 1600\, MeV$. If this were the case, and given the larger uncertainties that one would have now in the evaluation of MEC, the extraction of information about quark exchange effects would be equally problematic. However, in view of the roughness of this estimate the validity of the former assertion is at least questionable. However, this region of higher energies faces difficulties of another type given the smallness of the cross sections and the relative large background as we pass to evaluate.

In fig. 10 we show the results for the cross section from QEC and from the background. The background has been calculated as follows. Around values of $\sqrt{s}$ where the Δ excitation model provides a good $(e, e'\pi)$ cross section the model of section 6 is used. When discrepancies with experiment appear then the following procedure is used. Based on the fact that in the background cross section studied in section 6 one can factorize out the cross section for $\gamma_v N \to \pi N$, we correct the predictions for the background with the Δ excitation model by multiplying these results by the ratio of the experimental $\sigma(\gamma_v p \to \pi^0 p)$ to the theoretical cross section with the Δ excitation model. The data for $\sigma(\gamma_v p \to \pi^0 p)$ are incomplete. We take them as a function of $\sqrt{s}$ for a fixed value of $q^2 = -1\, GeV$. This value of q^2 is suited to a broad region of values of T_p as can be seen from Fig. 8. At $T_p = 800\, MeV$, $q^2 = -0.94\, GeV^2$ and at $T_p = 1.25\, GeV$, $q^2 = -1.5\, GeV^2$. Even at $T_p = 1.8\, GeV$ the value of q^2

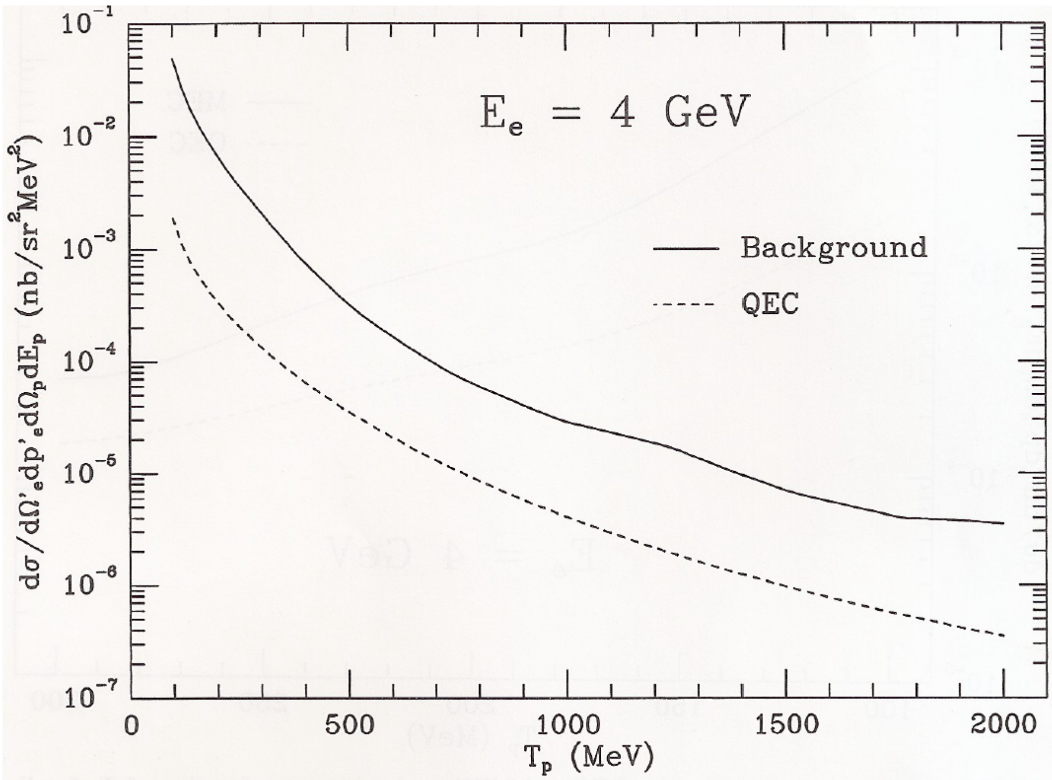

Figure 10: Differential cross sections for the QEC and background mechanisms as a function of T_p for $E_e = 4\,GeV$.

is not too different, $q^2 = -2.2\, GeV^2$. Hence our method to determine the background is quite reliable.

Coming back to Fig. 10 we observe that around the Δ peak the background is about 25 times bigger than the signal from QEC. For values of $T_p \simeq 300\, MeV$ ($\sqrt{s} \simeq 1300\, MeV$) it is about 15 times bigger. For values of $T_p \simeq 500\, MeV$ to $1800\, MeV$ ($\sqrt{s} \simeq 1350\, MeV$ to 1600 MeV) the background stabilizes around values which are 7 to 8 times bigger than the signal from QEC.

Comparison of the MEC contribution and the background in the resonance peak shows that MEC is about 1/4 - 1/6 of the background. We recall now that about 1/2 of the MEC contribution came from the pion on shell and qualified as a two step process of $(e, e'\pi)$ followed by πN scattering on the second nucleon producing a Δ. This means that this contribution is about 1/10 of the background wich comes from $(e, e'\pi)$ without a rescattering. This result is in qualitative agreement with features of multiple scattering in the deuteron [11].

Since the MEC contribution is sizeable compared to the background in the Δ region one may wander about how much the numbers in Fig. 10 can be altered by the interference. We have checked that, for energies around $T_p = 300\, MeV$ ($\sqrt{s} = 1300\, MeV$), the interference of MEC and background would reduce the background by about 30% with a tendency to produce a smaller reduction when one goes to higher energies.

The presence of the sizeable background in this reaction puts serious obstacles to the eventual performance of an experiment to determine the quark exchange signals. The signal would have a Δ-resonance shape in the E_Δ variable as seen in eq. (11), while the background does not have a resonant shape. The identification of the signal requires a high precision experiment to see a signal on top of a background about an order of magnitude larger. On the other hand it requires to measure a sufficient number of points by changing q^0 and q such as to determine the resonant shape of the signal on top of the background. The resonant shape could be better determined by looking at the invariant mass of the πN system which would require and extra coincidence measurement of the Δ decay products, with extra burden on the experiment. In order to set some scale about the difficulties of the experiment let us recall the present state of art at Mainz where in the related $d(e,e'p)$ reaction (with no π production) one measures a cross section of $4 \times 10^{-4} nb/sr^2 MeV$ with 3% statistics in about 10 h. At $T_p = 1300\, MeV$ the signal from QEC is $1.6 \times 10^{-6} nb/sr^2 MeV^2$ and many points would have to be measured to determine a resonant shape on top of the background. The calculations have been done at $E_e = 4\, GeV$ having in mind CEBAF as a likely facility. However, it is clear that even at this facility, where the luminosity will be three times bigger than at Mainz, the amount of time required for such an experiment would be extremely large. This, together with the likelyhood of a confusion between genuine quark effects and meson exchange currents does not give in our opinion, great hopes to this reaction as a tool to investigate quark effects in nuclei.

8 Conclusion.

Following an idea suggested in refs. [1, 2, 3] to look for QEC effects in the $d(e,e'p)\Delta$ reaction with the Δ produced at rest and a fast nucleon, we have evaluated the cross section for this reaction using the QEC mechanism and also the competing MEC mechanisms. We have also evaluated the background which one would meet in an eventual performance of the experiment. Our conclusions can be summarized as follows:

i) We observed that in the present reaction the excitation of preexisting virtual delta to real deltas due to QEC forced the transfer of a fairly large amount of energy to the delta, which is not envisaged in the impulse approximation. The defficiencies showed up in a frame dependence of the cross section. Since the QEC signals are calculated in the deuteron frame rest where they have a maximum value, they should be considered as an overestimate, however not by a large amount, something of the order of 30 %. Also off shell effects in the amplitude due to this transfer of energy are supposed to lead a reduction of the cross section by yet an uncertain amount.

ii) We showed that the MEC with pion exchange were extremely sensitive to retardation effects, which increased the MEC cross section by a factor of about 350 with respect to a static calculation. Similarly this showed that the notion of preexisting $\Delta' s$ due to pion exchange and calculated in a static approximation is unsuited to the study of reactions like the present one, with a fairly large amount of energy transported by the pion.

iii) At excitation energies around the Δ region the MEC cross sections are larger than the QEC ones and the background is about 10-20 times larger.

iv) At bigger energies, rough estimates indicate a tendency to balance the quark and meson exchange currents effects, with large uncertainties in the MEC which would make difficult the identification of genuine quark effects.

v) In all the range of energies $1\,GeV \leq T_p \leq 2\,GeV$ the background is about 7-9 times larger than the signal from QEC. At lower energies the ratio of background to QEC is even bigger.

vi) The cross sections for the signal of QEC for $T_p > 1GeV$ are smaller than $4 \times 10^{-6} nb/sr^2 MeV^2$. This, together with a large background present in the reaction, which would force measurements with high precission in a broad energy region in order to identify a delta peak on top of a background, puts severe technical limits to the eventual study of genuine quark effects with the present reaction.

We would like to acknowledge Dr. L. Ya. Glozman for providing us with the $\Delta\Delta$ wave function and its normalization and for multiple discussions. We also thank Prof. A. Faessler for discussions. One of us, J.A.G. wishes to acknowledge finantial help from IVEI and E.O. from the Humbold Foundation. This work is partially supported by CICYT, contract number AEN 93-1205.

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