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A. Jurewicz and L. Satta: A MODEL FOR FINAL STATE INTERACTIONS IN PHOTOPRODUCTION OF π^o ON DEUTERIUM IN THE $\Delta(1236)$ RESONANCE REGION.

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A. Jurewicz[(x)] and L. Satta: A MODEL FOR FINAL STATE INTERACTIONS IN PHOTOPRODUCTION OF π^o ON DEUTERIUM IN THE Δ(1236) RESONANCE REGION. -

In the last few years many new data on single pion photoproduction on deuterons become available in the resonance region[(1÷4)].

These measurements have been traditionally analyzed in terms of the spectator model. The results seem to be in some cases in disagreement with earlier data on photoproduction off free protons and with theoretical predictions. In search for possible sources of the discrepancies the presumed existence of exotic electromagnetic currents, and a possible violation of time reversal invariance in electromagnetic interactions has been extensively discussed[(5)].

We do not intend to dwell on such problems here. Our aim is to study possible corrections to the spectator model due to genuine final state interactions (as contrasted to corrections arising e.g. from the Pauli exclusion principle, which reduces the phase space available to a pair of nucleons in the final state[(6)]). The reaction $\gamma d \rightarrow \pi^o p n_s$ seems most convenient for such a study. Singlet and triplet states are allowed in the final np system and Coulomb effects in the final state are absent.

For the process in question there exist recently measured π^o differential cross sections in the first resonance region[(1,2)]. Taken at face value they show a suppression of the cross section by about 20% with respect to data for the reaction $\gamma p \rightarrow \pi^o p$. If the interpretation of the data is correct, we have an indication that in the first resonance energy region the spectator model can not be taken for granted.

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The model which we present below explains the above mentioned suppression as being due to final state interactions.

The model has been intended to be as simple as possible, especially in treating the kinematics of the whole problem, in order to avoid extremely tedious calculations. Our study may serve therefore rather as a guide to further more refined investigations. Nevertheless it is quite surprising that final results fairly agree with available data.

We start from the matrix element for the reaction $\gamma d \to \pi N N$ written in the form

$$\text{(1)} \quad \langle f|T|i\rangle = \langle f|(T_{\gamma p} + T_{pn} G_o T_{\gamma p} + T_{\pi n} G_o T_{\gamma p} + \ldots + (n \leftrightarrow p))|i\rangle$$

where the initial state represents a deuteron with momentum distribution of the nucleons given by the Gartenhaus S-wave function[7], and the final state consists of a neutron (n), proton (p) and a π^o. The function G_o describes the propagation of the three particles (p, n, π^o) in the intermediate state, and $T_{\gamma p}$, T_{pn}, $T_{\pi n}$ are operators for photoproduction, neutron-proton scattering and π^o-neutron scattering, respectively. They are of course two particle operators acting in three particle space[(x)]. Analogous terms with neutron and proton exchanged among themselves are represented by $(n \leftrightarrow p)$.

For sake of simplicity we do not want to get into the extremely complicated problem of the off-shell continuation of T matrices calculated between intermediate and/or final and initial states. Especially there are almost no indications as to a possible off-shell continuation of $T_{\gamma p}$. We approximate therefore G_o by $i\pi\delta\,(E_i - E_{int})$ where E_i, E_{int} are energies in the initial and intermediate states respectively, thus neglecting contributions due to the principal value. Our kinematical simplification consists in performing averages over spin and isospin degrees of freedom in $T_{\gamma p}$, T_{pn}, $T_{\pi N}$ so that e.g. the record of spins of the interacting particles remains only in their angular distribution. The problem of relative phases of amplitudes, as we shall see below, is simplified by the fact that we confine ourselves to photon energies in the region of formation of the Δ(1236) resonance.

With the above assumptions we get from (1) the differential cross-section in the following form:

$$\text{(2)} \qquad d\sigma = d\sigma_o^{(p)} + d\sigma_N^{(p)} + \sigma^{(p)} + (n \leftrightarrow p) + \text{interference terms}$$

(x) - A detailed description of kinematics for reactions involving deuterons can be found in ref. (8).

which by suitable integration over variables pertaining to the three-particle final state provides us with all desired distributions, which may be e.g. the angular distribution of the emitted π^o, the momentum distribution of one of the final nucleons, invariant mass distributions etc. The terms $d\sigma_o^{(p)}$, $d\sigma_N^{(p)}$, $d\sigma_\pi^{(p)}$ arise from appropriate squaring of $T_{\gamma p}$, $T_{pn} G_o T_{\gamma p}$, $T_{\pi n} G_o T_{\gamma p}$ ("proton source" matrix elements) respectively. Analogous "neutron-source" terms are denoted by ($n \leftrightarrow p$).

As to interference terms, they can be divided in two classes. The first class includes terms arising from interference of the just mentioned "proton-source" matrix elements among themselves. Similar terms will also arise from "neutron-source" matrix elements[8]. Now, from the calculated shape of the invariant mass spectrum of the intermediate p-n state we deduce that most important contributions to (2) come from the energy range where T_{np} matrix elements have relatively small imaginary parts. This is due to the fact, that in this range the decreasing S wave phase shifts are already quite small. On the other hand the $T_{\gamma p}$ matrix element is essentially imaginary since it is calculated at energies close to the Δ (1236) resonance. The interference term[8] should therefore be quite small. As to interference terms containing $T_{\pi n}$ matrix elements, our calculations show that they contribute very little to the final cross section.

We conclude therefore that interference terms of this class are relatively small in the Δ (1236) region, and we shall skip them. This approximation will of course get worse, the more we go away with photon energy from the resonance region.

Terms of the second class arise from interference of the "proton source" terms with the "neutron-source" ones. An estimate of their importance is more difficult and is strictly connected to the way in which distinction between "proton-source" and "neutron-source" events is made in an experimental set up. At photon energies of a few hundred MeV the identification of a, say "proton-source" event is based on the assumption that the probability for such an event of finding a neutron with high momentum in the final state is strongly suppressed by the deuteron wave function[1,2]. This reasoning is true for a "pure" spectator model. We assume that it remains essentially valid also in the situation here discussed, since in our model the momentum distribution of the "spectator" nucleon remains strongly peaked for small momenta. Terms arising from interference between "proton-source" and "neutron-source" amplitudes should therefore be of small importance. Were it not the case, any direct comparison of data on $\gamma d \rightarrow \pi^o p n_s$ with those on $\gamma p \rightarrow \pi^o p$ would be useless.

To conclude, in our calculation we shall take into account only the first three terms of (2).

The mechanism of the reaction as described by our model, may be summarized as follows (see Fig. 1). The initial photon strucks the proton whose momentum distribution in the d rest system is given by the S-wave Gartenhaus function. The resulting p π^0 system in its c.m. frame has the known angular distribution of photoproduction on free protons. Close to the $\Delta(1236)$ resonance this angular distribution can be approximated by 5-3 $\cos^2\theta$. The pion, the proton and the spectator neutron then move as real particles toward rescattering, or can escape out from the interaction region. The probability of interacting in the pn (or π^0n) subsystem depends on the value of the scattering cross section of the given subsystem.

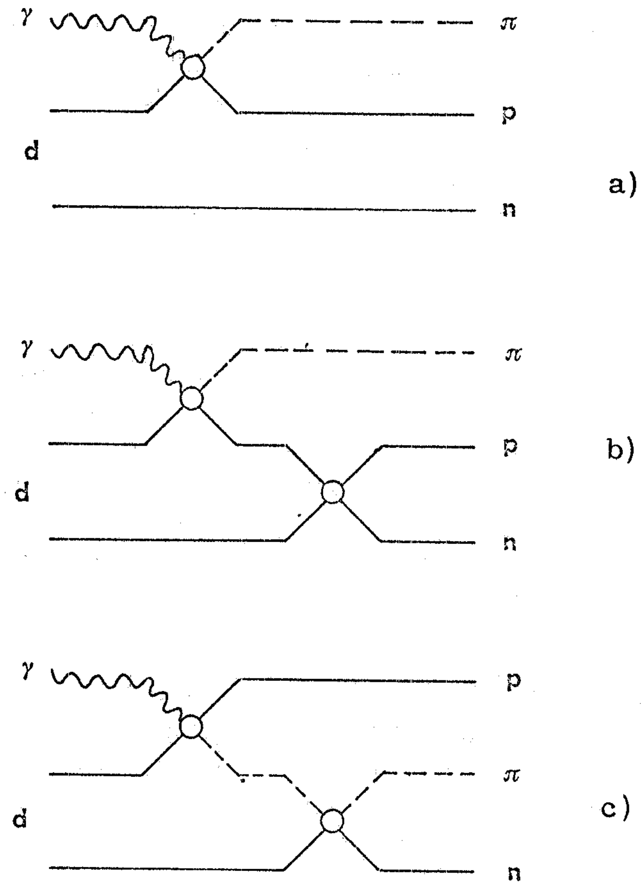

FIG. 1

After rescattering the angular distribution in the c.m. of the subsystem is that of πn (or pn) scattering at respective energy. The particles could then rescatter again, but we do not include this possibility in our calculations, since our numerical results indicate that contributions from double rescattering (and higher order processes) would be very small in the energy range discussed here. We do not think it reasonable to include such small effects into our extremely simplified model. Numerical calculations have been performed by the Monte Carlo method for initial photon momenta of 270, 320 and 350 MeV/c.

We have found the calculated ratio of differential cross sections

$$R = d\sigma\,(\gamma p \to \pi^{o} p)_{D_2} / d\sigma\,(\gamma p \to \pi^{o} p)_{H_2}$$

quite satisfactory when compared to available data[1,2]. Nevertheless we have tried to improve further the results (but not to fit them to available data!) by assuming that the rescattering processes (as shown in Fig. 1b), c)), as being due to short-range interactions, actually take place within the "central part" of the deuteron. This has been approximately accounted for by multiplying the rescattering terms of Fig. 1b) and 1c) by the probability that the initially bound nucleons stay inside a sphere of 3 fm radius. The contributions of the diagram of Fig. 1a) are therefore enhanced.

In what follows we shall refer to predictions resulting from calculations in this last version.

Our calculations show that rescattering corrections almost completely arise from p-n interaction. This is clearly due to large σ_{np} cross sections as compared to $\sigma_{\pi^{o}n}$.

We fix our attention on two kinds of histograms which seem most indicative to us. These are the momentum distribution of the "spectator" nucleon (Fig. 2a) and the angular distribution of π^{o} (Fig. 2b). We compared the calculated momentum distributions of the "spectator" nucleon as obtained from our model with those resulting from the pure spectator model. The angular distributions of the final π^{o} have been compared with the corresponding distribution for neutral photoproduction on free protons.

As an example of π^{o} angular distribution we present the calculated results at 320 MeV/c, compared to the angular distribution of π^{o} photoproduced on free protons. The effect of p-n rescattering is seen to produce strong modifications with respect to the latter distribution. The suppression of the differential cross section at backward angles is in agreement with data, as will be seen. On the other hand the rise in the differential cross section at forward angles seems to be too steep and unnatural. We think that this rise may be due in part to the fact that our model does not account for inelasticity arising e.g. from rescattering processes leading to final states other than π^{o}pn.

Finally, we report in Fig. 3 the values of the ratio $R = d\sigma\,(\gamma p \to p\,\pi^{o})_{D_2} / d\sigma\,(\gamma p \to \pi^{o})_{H_2}$ calculated at c.m. angles for which data are available[1,2]. We find the agreement surprisingly good as for such a simple model the more that, as already was told before, no attempt has been made to fit these data. A decrease in the calculated ratio R at 270 MeV may be attributed to the fact that at this energy the interference terms become more important.

It would be desirable to have more data, especially at forward

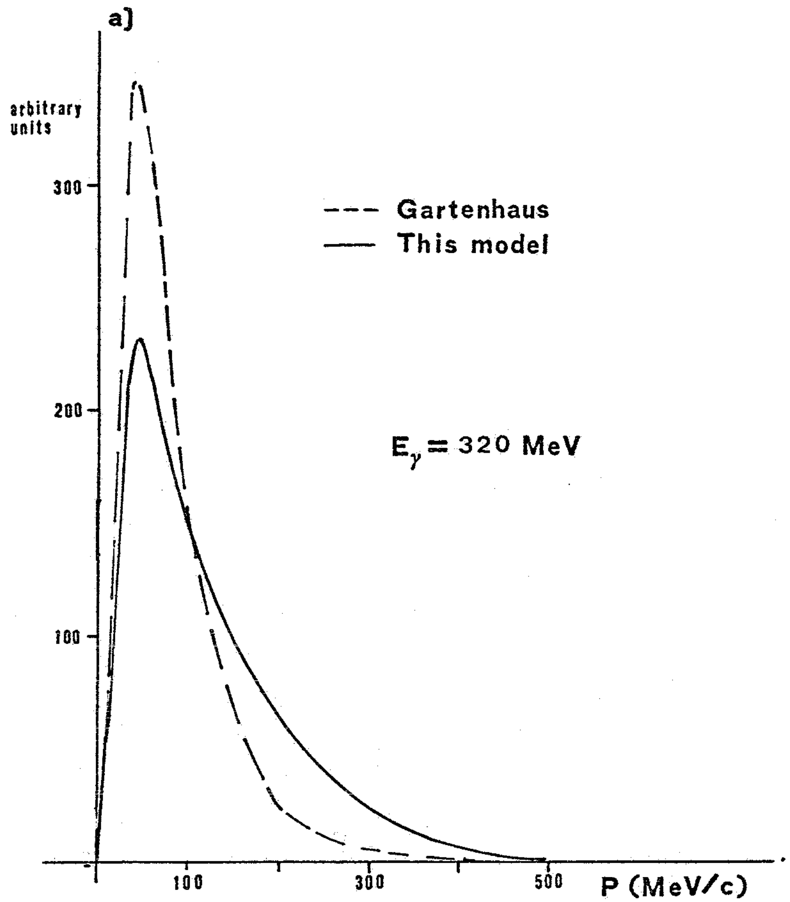

FIG. 2a) - Momentum distribution of the "spectator" nucleon.

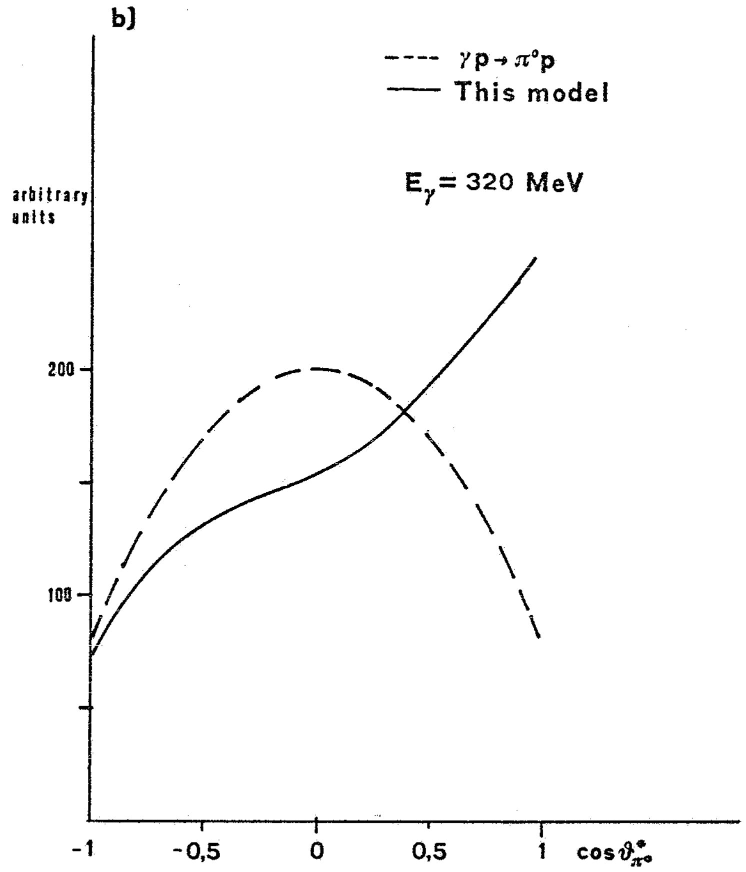

FIG. 2b) - Angular distribution of π^0.

angles, in order to check whether the dynamical mechanism proposed by us is really valid. One could then think about further refining the calculation.

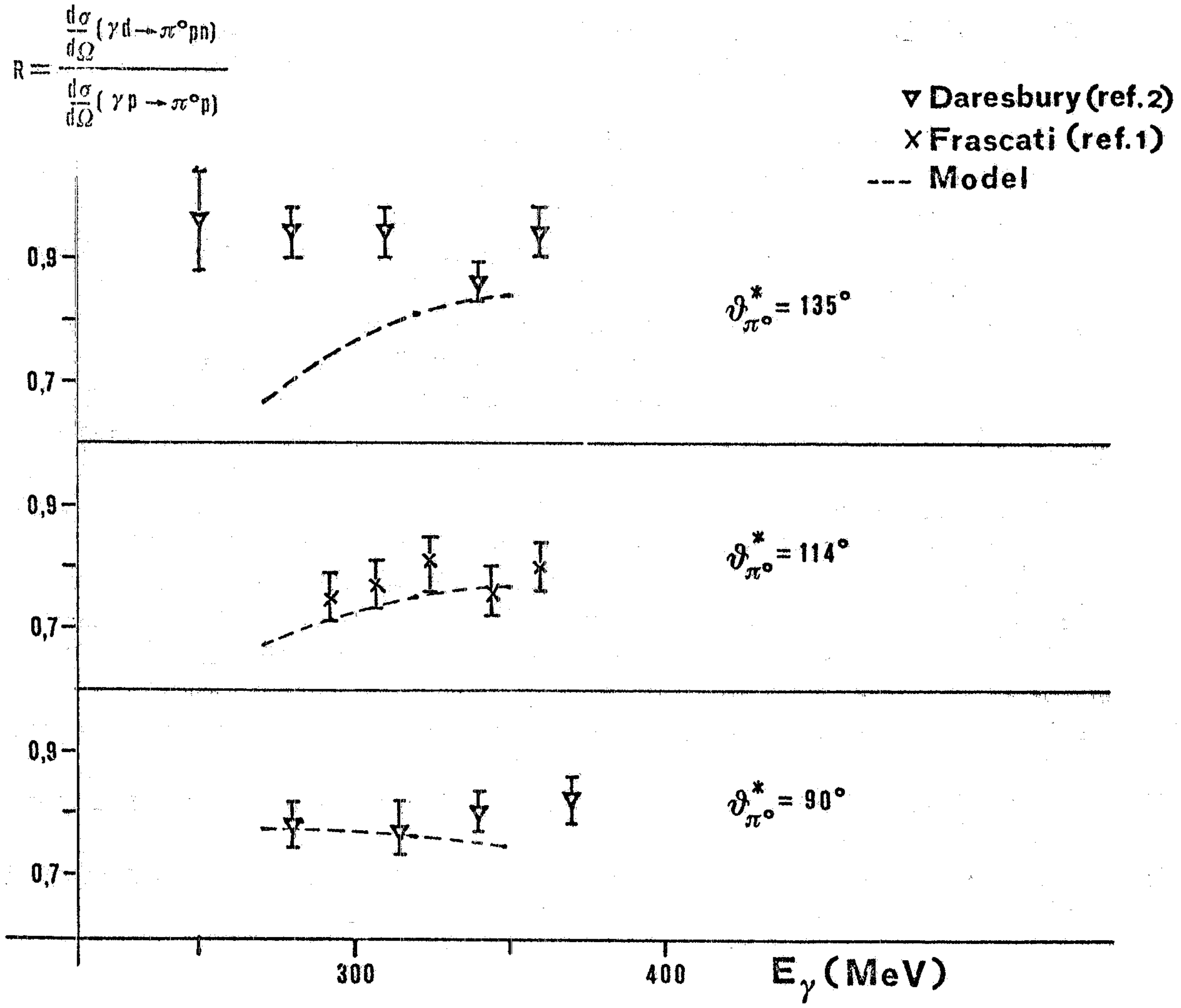

FIG. 3 - Ratio of differential cross sections for π^o.

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