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PHOTOPION PRODUCTION FROM NUCLEI IN THE ENERGY REGION OF THE Δ RESONANCE

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An intermediate energy nuclear physics experiment will provide some information on three main topics which are often strongly interconnected. First, from a classical nuclear physics point of view, the incoming particle will induce some reactions specific of the elementary field involved and will be sensitive to different components of the nuclear wave function.

The second and perhaps more fundamental approach is the elementary interaction itself : is this interaction the same on the bound nucleon inside the nucleus as in the free case? The simplest description of the reaction mechanism is to assume that the interacting nucleon is far enough from the others to behave as if it is free, and to use the impulse approximation. The study of quasi-free reactions can be a good test of this problem if it is performed on a nucleus on which the wave function is well known. The distortion of the ingoing and outgoing particles waves also needs to be reasonably known by other reactions in order to take into account these effects in a distorted wave impulse approximation (DWIA). We have to point out that we can extract much more precise information in a double arm measurement in which one detects the products of the elementary reaction such as $(\gamma,\pi\, p)$ than in a single arm one as (γ,π). In the first case, we should be able to determine the momentum of the recoiling system, which is exactly the opposite of the one of the interacting nucleon before the reaction in a quasi-free reaction. The invariant mass of the (πp) system, which is a very important parameter, can be explicitly measured. On the other hand, the experimental simplicity of the single arm measurement leads to a more complicated analysis because it implies an integration over a large phase space in momentum distribution where the π-nucleon invariant mass varies and so does the elementary cross sections. Therefore a coincidence measurement will be more precise in the comparison of an interaction with a bound nucleon to the same with a free one.

The third question is related to the behavior of the excited nucleus when the internal degrees of freedom of the nucleons are significantly involved in the reaction, i.e., when a pion is present. How does the initial excitation propagate in the nucleus? Instead of a quasi-free process, we are considering reactions in which two or more nucleons are involved. For instance, let us consider real Δ resonances created inside the nucleus, induced by pions or photons ; the Δ will have a reasonably small momentum relative to the remaining nucleus. With the Fermi notion it is possible to create a Δ which is at rest in the center-of-mass system of the remaining nucleus. Here we have a good tool to study the nucleon and nucleus Δ interaction. Some theoretical works are now in progress by Arenhovel on the Δ-nucleon system[1], Huber and Dillig[2] on more complex systems, and also by Moniz[3] who is investigating the Δ propagation in nuclei.

An "ideal" experiment

If one wants to separate the different aspects of the problem, and to learn something about the interaction inside a nucleus, it is necessary to choose a nucleus in which the nuclear wave function is well known.

The second point is that the distortion of the outgoing particles should be known, so we need data on the π and p scattering on the remaining nucleus after the reaction. But obviously, the lighter the target nucleus is, the smaller the distortion effects will be.

Then we have to try to separate quasi-free and non quasi-free reactions. The first process will be very likely if the recoiling momentum is small, and it is assumed to decrease like the known fall-off in single momentum component of bound nucleons. On the other hand, if the transferred momentum is shared by several nucleons in a non-quasi-free process, the variation of the cross section as a function of P_R should be less rapid than in the quasi-free one. So the probability of detecting such processes will certainly be higher at large values of P_R. Then low P_R measurements will mainly check the elementary interaction and the quasi-free related processes ; we expect also that large P_R will give information on the non-quasi-free ones.

The experimental set-up

We will need in the experiment described in this paper to detect a proton and a pion emitted from the target in coincidence and measure their momentum. This was achieved by the photon Saclay facility (Fig. 1) described in ref.[4]. The Bremsstrahlung photon beam

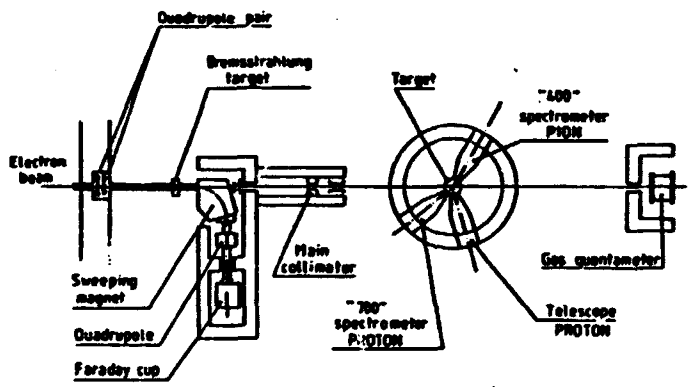


Fig. 1

is produced by the analysed electron beam on a 1/100 radiation length copper target. A sweeping magnet pull out the electrons from the photon beam defined by a set of collimators. The photon flux is monitored by a gas quantameter. Three spectrometers rotate around the liquid target (D or ^4He). The pion is detected in the 400 MeV/c magnetic spectrometer (solid angle 3.2×10^{-3} sr, $\Delta p/p = 9$ %) and the proton either in the 700 MeV/c magnetic spectrometer (solid angle 2.3×10^{-3} sr, $\Delta p/p = 12$ %) or in a range telescope (solid angle $28. \times 10^{-3}$sr, $\Delta p/p = 15$ % for 100 MeV protons). The particles are identified by their energy loss in plastic scintillator hodoscopes, and a time to digital converter measures the differences in time of flight between the target and the proton and pion detectors. The muon contamination in the pion spectrometer is determined by a range measurement.

The $\gamma D \to p p \pi$ reaction

Let us consider the reaction :

$$\gamma + D \to p + p + \pi^- .$$

Experimentally it is a very favourable case : the three final state particles can be easily detected and their momentum measured, if their energy allows them to escape the target. It is very likely that at least two of them can be detected, and so even if a Bremsstrahlung photon beam with a continuous spectrum is at your disposal, you will be able to determine all the kinematics, so the energy of the interacting photon[4]. If now you have a monochromatic photon beam, by detecting one of the particles you can measure directly the missing mass spectrum of the two undetected particles. What can be said on this reaction ? First the most likely to occur is the absorption of the photon by the neutron and emission of a π nucleon pair, which are very often coupled to a Δ resonance (if the γ energy is close to 300 MeV), the proton remaining spectator (Fig. 2). This quasi-free photo-production is characterized by the invariant mass Q of the produced π^-p pair, the angle ω between the π and the photon in the rest frame of the πp system (Fig. 3) and the momentum of the spectator nucleus.

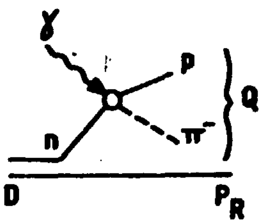


Fig. 2

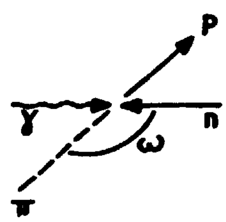


Fig. 3

In this quasi-free process, if $\vec{p}_O$ is the momentum of the neutron before the reaction we have obviously

$$\vec{p}_R = \vec{p}_O.$$

We can describe this reaction by the impulse approximation and the differential cross section is then proportional to the elementary cross section $d\sigma_n/d\Omega_\pi(Q,\omega)$ multiplied by the momentum distribution $\rho_D(p_O)$ in the deuterium

$$d\sigma = A \frac{d\sigma_n}{d\Omega_\pi} (Q,\omega) \ \rho(|\vec{p}_R|). \qquad (1)$$

A is a kinematical factor.

We did two kinds of measurements. In the first, we left the direction of $\vec{p}_R$ constant and changed Q in order to check the π-p mass distribution. In order to have a comparison with the quasi-free model, we use the reduced cross section $d\sigma/d\Omega_\pi$.(In the helium-4 case we used a distorted momentum distribution calculated by the DWIA method[4] $\rho'(p_R)$ instead of $\rho(p_R)$ taking in account the distortion of the pion and proton waves by the 3 nucleons system). We define it as :

$$\frac{d\sigma}{d\Omega_\pi} = \frac{1}{A \ \rho(p_R)} \frac{d\sigma}{d\Omega_\pi dp_R}. \qquad (2)$$

In the quasi-free case, this reduced cross-section is of course the free nucleon one. The second kind of experiment is an angular distribution. There Q, ω and p_R stayed constant and we measured the cross section as a function of θ_R, the angle of the recoiling system. Again, we compare the measured cross section to the quasi-free one by the quantity :

$$f(\theta_R) = \frac{\dfrac{d\sigma}{d\Omega_\pi dp_R}}{A\ \rho(p_R)\ \dfrac{d\sigma_\pi}{d\Omega}\ (Q,\omega)} \qquad (3)$$

which is equal to unity in the quasi free model.

As we are working on relatively low values of $|p_R|$, where the deuteron wave function is precisely known, we detected the proton p and the π^-. We have also to take in account diagrams in which p is the spectator nucleon. But these diagrams give negligible contributions because :

i) $|p|$ is large, so $\rho_D(p)$ is small ;

ii) the kinematics is chosen in such a way that the proton p_R is emitted on the same side as the pion, and their invariant mass small and not far from threshold. Another consequence of this kinematics is to minimize the Pauli principle effects as the two protons direction is very large.

For $|p_R| = 50$ MeV/c, we found a very good agreement with the quasi-free model qualitatively and quantitatively* for the Q variation (Fig. 4) and for the θ_R angular distribution (Fig. 5). But if $|p_R|$ increases, the picture changes. This was of course expected because then $\rho(|p_R|)$ decreases strongly and more complicated processes may appear. For instance (Fig. 6) at $|p_R| = 150$ MeV/c, the θ_R angular distribution is far of being isotropic. The uncertainties on the quasi-free cross section, mainly due to the deuterium wave function are less than 10 % and affect only the position of the horizontal line describing this process, not the shape.

In order to interpret these data, we included some second order processes. The pion rescattering (Fig. 7a) is responsible for the backward bump, and the pp rescattering (Fig. 7b) term enhances the cross section because their relative kinetic energy decreases. This gives a qualitative agreement with the data (full line Fig. 6) but before trying more complicated processes,

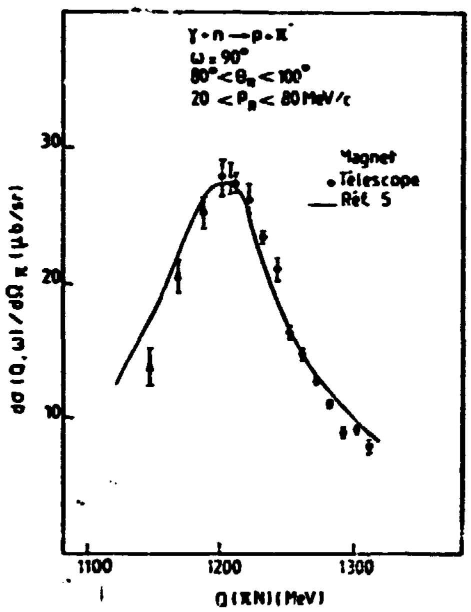


Fig. 4

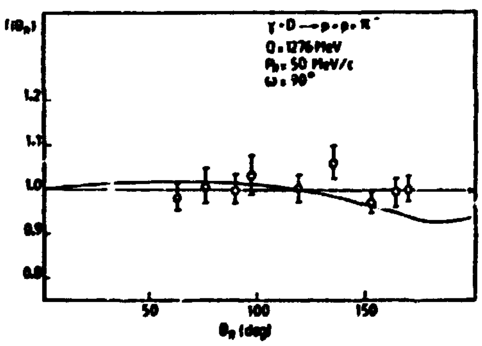


Fig. 5 - The solid line shows the contribution of the pion and nuc lear rescattering.

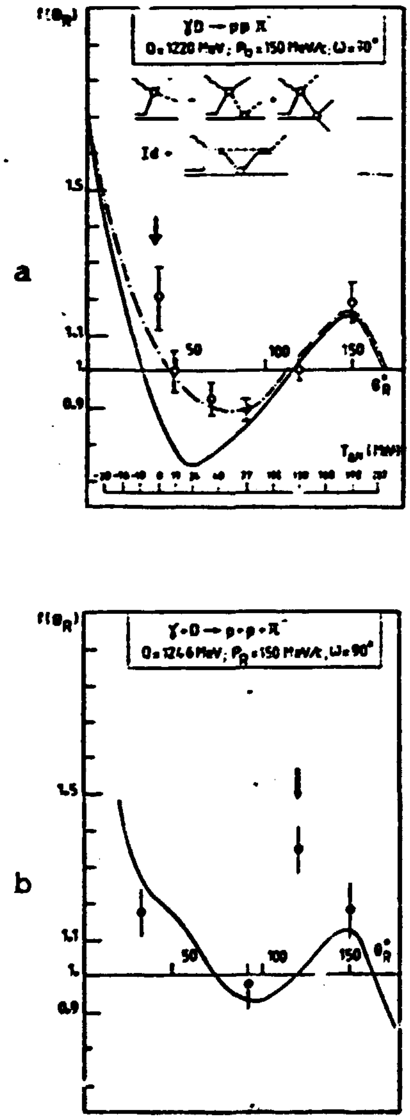
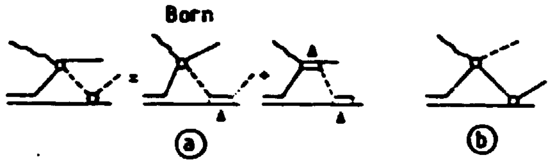


Fig. 6 - The angular distribution $f(\theta_R)$ on deuterium for p_R = 150 MeV/c, Q = 1226 MeV a) and Q = 1246 MeV b). The full line curve represent the prediction of the quasi free model + $\pi\mathcal{N}$ rescattering + $\mathcal{N}\mathcal{N}$ rescattering. The dotted dashed curve represent the prediction of the contribution of the two loops diagram, part of a $\Delta\mathcal{N}$ rescattering process. The arrow correspond to dibaryonic masses $Q_{NN\pi}$ = 2.16 GeV (a) and $Q_{NN\pi}$ = 2.25 GeV (b).

we wanted to check the π rescattering contribution. Considering this process, it is described by the two diagrams shown in Fig. 7a because the πN scattering amplitude is dominated by the Δ. It is a way of



measuring the exchange part of the Δ-N interaction.

Fig. 7

The corresponding amplitude must be large when the intermediate pion is on the mass shell. As we have to perform an integration over the momentum in the triangular part of the diagram, the larger the kinematical region allowing an intermediate on-mass shell pion is, the maximum the effect will be. So we have chosen, in a third experiment, to measure the θ_R angular distribution in order :

i) to minimize the quasi-free process, which means a large value of $|p_R|$;

ii) by a large relative energy of these two particles to suppress the proton final state interaction ;

iii) to favourize the Δ production.

As p_R becomes large, it is possible then to detect the two protons. The result[6], presented on Fig. 8, shows the ratio of the measured yield for $Q = 1200$ MeV, $\omega = 90°$ and $|p_R| = 400$ MeV/c to the quasi-free prediction (using the Reid soft core wave function). The experimental points present very large deviation with this model, represented by the dotted line. The solid line, strongly peaked around $\theta_R = 45°$, is the result of the calculation including now the π rescattering term. It gives qualitatively the description but there is still something missing specially for large angles. I give on Fig. 8, the mass scale of the two protons system and the discrepancy between the experience and the solid line increases with this mass. This was a guide to

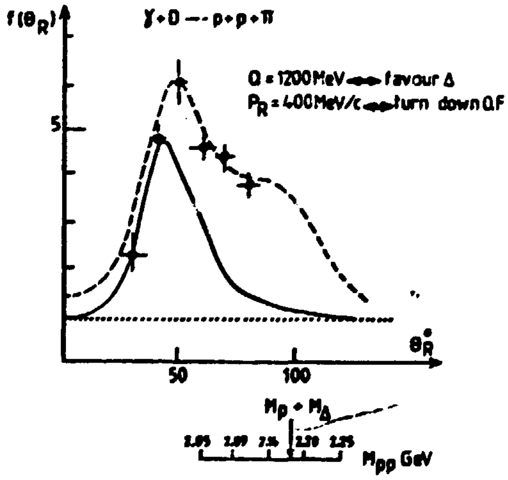


Fig. 8

consider the contribution of a diagram (Fig. 9) similar to the double pion photoproduction on a nucleon followed by the reabsorption of one of the pions (like in the deuterium photodisintegration). Adding this new process leads to the dashed curve, in good agreement with the data.

Then we tried to have a direct proof of the validity of such a diagram. We have changed the kinematical conditions :

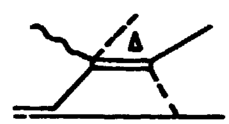


Fig. 9

i) increasing again $|p_R|$ to minimize again more strongly the quasi-free contribution: $|p_R| = 500$ MeV/c ;

ii) going far from the Δ resonance region to minimize also the π-rescattering process Q = 1100 MeV. This also vanishes the region for on-shell rescattering.

The corresponding angular distribution is again referred to the quasi-free photoproduction. The solid line represents the quasi-free plus rescattering contribution, and the dashed one the result obtained by adding the double pion production term.

The agreement with the experiment is excellent (Fig. 10) (note that it was necessary to introduce the exchange of the ρ meson and a form factor at each pion-baryon vertex to take in account the data[7]).

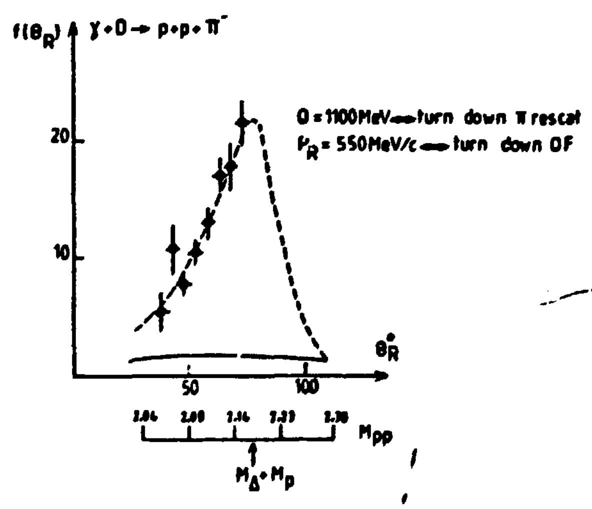


Fig. 10

The $\gamma^3He \rightarrow p\pi$ + 3 nucleons experiment

The situation is somehow more complicated now than in the deuterium case.

First the kinematics is not as well defined if one uses a Bremsstrahlung beam, and detects the pion and a proton. Then Q,ω and p_R, the component of p_R perpendicular to the photon beam are well determined. If the three nucleon system is in its ground state (^3He) the kinematics incompletely defined and let us call $E_{\gamma o}$ the corresponding photon energy and $p_{R//o}$ the parallel to the photon component of the recoiling momentum. If now the three nucleon system is in an excited state of energy E_x the corresponding value of E_γ and $p_{R//}$ are related by

$$E_\gamma - E_{\gamma o} \approx p_{R//} - p_{R//o} \approx E_x.$$

As the final state of the three nucleons is not measured an undetermination remains on E_γ and $p_{R//}$.

In order to limit the effect of this undetermination we carry our experiment under the following conditions :

i) we set the end point of the Bremsstrahlung 100 MeV above $E_{\gamma o}$ in order to integrate always on the same set of final state ;

ii) we left θ_{R_o} near 90° in order to minimize the effect of the uncertainty on $p_{R//}$ (they will be added quadratically to p_{R_o}). In fact, in a quasi four process, the final state is very likely an ^3He (we demonstrated this by changing the end point of the Bremsstrahlung from 100 MeV to 20 MeV above $E_{\gamma o}$: the cross section remains the same). So the kinematical parameters defining the quasi-free process (Q,ω,p_R) are fairly well under control.

The second difficulty comes from the final state interaction of the pion and the proton with the residual nucleus. They are taken in account by a distorted wave impulse approximation where the outgoing waves are distorted by an optical potential simulating (this includes the diagram of Fig. 7) the effect of the nucleus. The parameters of this model are fitted on the π and p scattering on ^3He. The cross section can be still factorized as in the plane wave approximation as in formula (1),

$$\frac{d\sigma}{d\Omega_\pi dp_R} = A \frac{d\sigma_N}{d\Omega_\pi}(\Omega,\omega)\rho'(p_R)$$ where $\rho'(p_R)$ is a distorted momentum distribution.

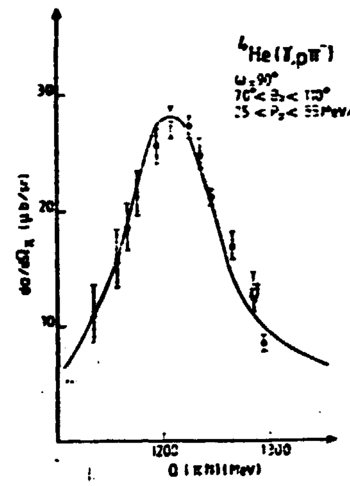


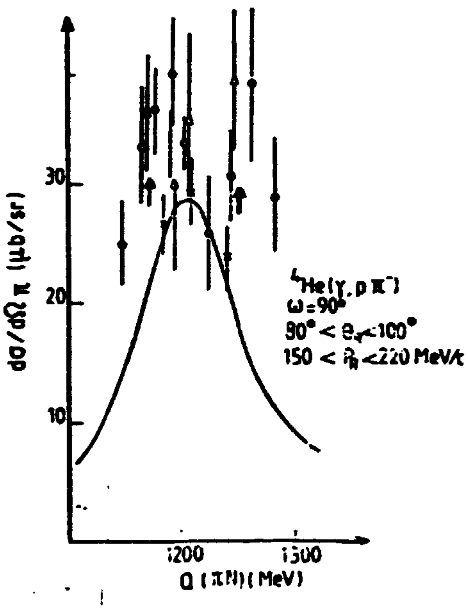
Fig. 11 - The reduced ^{4}He $(\gamma,p\pi^-)$ reaction cross section as a function of Q for $p_R = 50$ MeV/c. The solid curve gives the prediction of the quasi-free model (elementary cross section).

The results are shown in Fig. 11 for $p_R = 50$ MeV/c. The agreement with the DWIA predictions is excellent. But this is not true for p_R large. For $p_R = 185$ MeV/c we found the results of Fig. 12. The solid curve, the quasi free prediction, is very far from explaining the experimental results. We are able also to demonstrate that the excess of cross section corresponds to reactions in which the (NNp) recoiling system is in a break up state by changing the Bremsstrahlung end point. We found unexpected anomalies, varying in respect of Q when θ_R changes. The higher part may partially be explained by the diagram of Fig. 9 at $\theta_R = 90°$ and $70°$ but not at $\theta_R = 110°$.

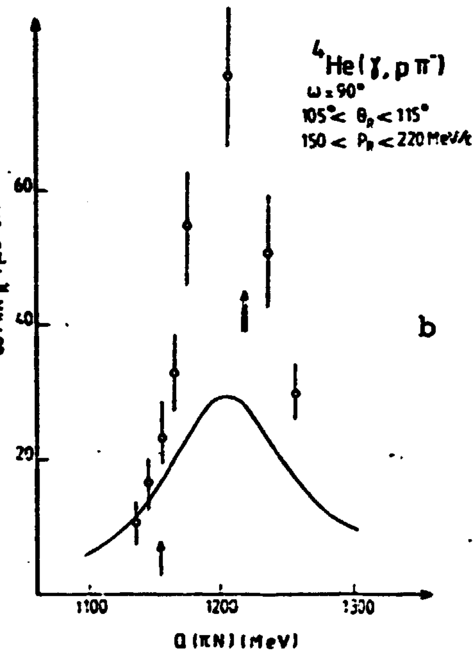
Possible interpretations of the anomalies

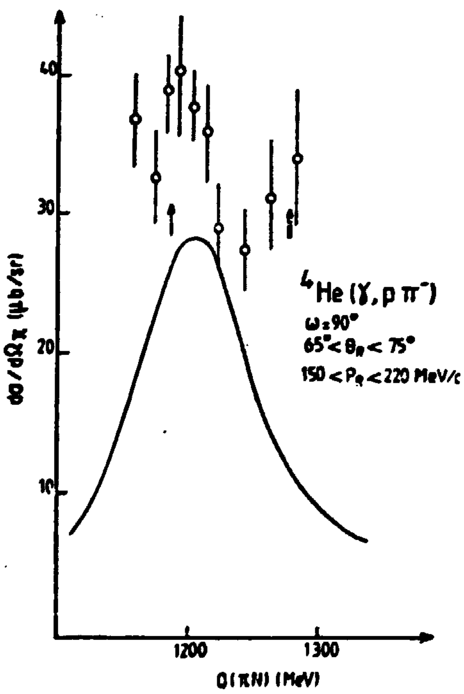
At this point, the situation is not fully satisfactory. It is obvious for the ^{4}He, but it is true also for the deuterium if we consider only the quasi-free processes and the diagram of Figs. 2, 7 and 9, which are under control. Starting from this firm basis, we have to make a choice between two ways :

i) we can try to interpret the discrepancies by more elaborated diagrams. For instance (noticing that the discrepancy on Fig. 6a is large for low value of the relative ΔN kinetic energy) let us consider a ΔN rescattering at low relative energy and assume that we can describe this interaction by the two loops diagram of Fig. 13. This will give the dotted dashed curve on Fig. 6a. It is able to predict the effects for other kinematical situation in order to check this model ; see for instance the dotted dashed curve of Fig. 14 ;



a





c

Fig. 12 - The reduced ^{4}He $(\gamma, p\pi^-)$ reaction cross section as a function of Q for $p_R = 185$ MeV/c for a) $\theta_R = 90°$, b) $\theta_R = 70°$, c) $\theta_R = 110°$. The solid curve gives the prediction of the quasi-free model (elementary cross section). The arrows correspond to dibaryonic states of $Q_{NN\pi} = 2.16$ GeV and 2.25 GeV. The cross points were taken with a Bremsstrahlung end point at $E_{\gamma 0} + 20$ MeV.

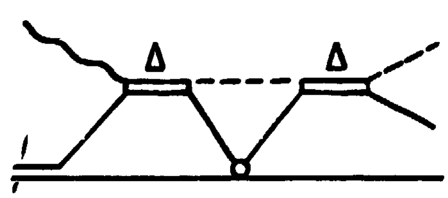


Fig. 13

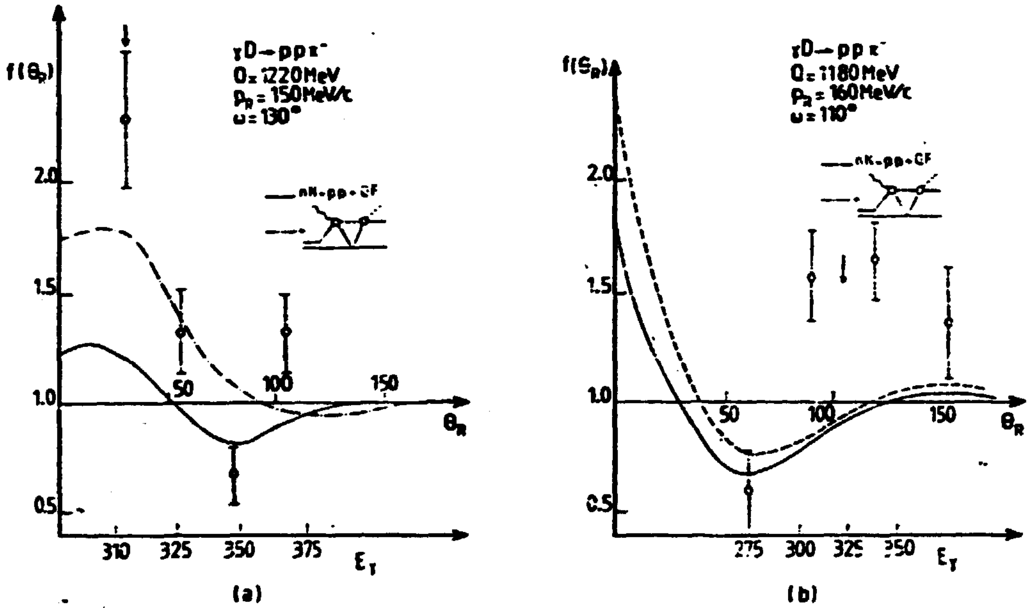


Fig. 14 - Angular distribution of .he D(γ,pπ⁻) reaction $f(\theta_R)$ for 2 kinematicals conditions : Q = 1180 MeV p_R = 160 MeV/c a) ; Q = 1220 MeV p_R = 150 MeV c). The $Q_{NN\pi}$ = 2.16 MeV dibaryon mass correspond to E_γ = 316 MeV.

ii) on the other hand it is tempting to consider in a more global approach the excitation of dibaryonic resonances. In this case, we can assume that the photon interacts with a pair of nucleons, the others remaining spectator. The recoil is then taken mostly by one nucleon and the kinematics is similar to the deuterium reaction. We can notice that the anomalies observed on ^{4}He and deuterium are consistent with two dibaryonic states of mass $Q_{NN\pi}$ = 2.16 GeV and $Q_{NN\pi}$ = 2.25 GeV, with width of the order of 30 to 60 MeV (arrows on Figs. 6 and 12). We must notice that several indications of dibaryonic states have been given recently on other reactions (see for instance polarized proton on polarized proton scattering where a relatively narrow structure has been found at $Q_{NN\pi}$ = 2.16 GeV[10]).

Experimental check of these interpretations

Returning to the angular distribution $f(\theta_R)$ on deuterium, we can change the initial kinematical condition in order to modify the contribution of the (ΔN) interaction, and have thus a signature of this process. If one considers now the dibaryonic point of view we have to notice that there is a relation between the angle θ_R and the energy of the photon inducing the reaction i.e. the invariant mass of the two baryons system. As the dibaryonic states manifestations are related to this mass they should appear on these experiments at the corresponding θ_R. By changing the set of constant parameters (Q, ω, p_R) we will change the angle where the dibaryonic state is expected.

Preliminary results

As we pointed it out before the study of the angular distribution $f(\theta_R)$ can be a check of possible dibaryonic states as θ_R and E_γ are correlated. For instance a dibaryonic resonance of mass $Q_{NN\pi} = 2.16$ GeV must appear at $\theta_R = 90°$ if the invariant mass Q of the $\pi\mathcal{N}$ system is 1.18 GeV and $\theta_R = 40°$ for $Q = 1.22$ GeV, the recoiling nucleon having a momentum $p_R = 150$ MeV/c.

On the other hand the $(\Delta\mathcal{N})$ contribution is presented taking in account the mixed scattering diagram of Fig. 13 (dotted-dashed curve). The solid curve is the quasi free + $\pi\mathcal{N}$ + $\mathcal{N}\mathcal{N}$ contribution (Fig. 14).

The preliminary data do not support the $\Delta\mathcal{N}$ rescattering interpretation. This leads to the conclusion that the present $(\Delta\mathcal{N})$ calculation cannot explain also the anomalies on deuterium. But the excess of cross section is consistent with the existence of a $Q_{NN\pi}$ = 2.16 GeV state with a width of the order of 50 MeV.

We have also recently completed the measurement done at $p_R = 150$ MeV/c, Q = 1246 MeV and the new points are reported on Fig. 15. They agree with the previous results and confirm an anomaly around a dibaryonic mass $Q_{NN\pi} = 2.25$ GeV as in the helium-4.

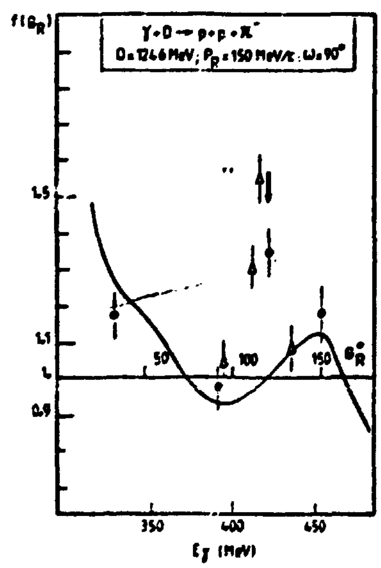


Fig. 15 - The triangles are recents experimental results.

As a temporary conclusion, this work being in progress, we are able to explain the largest part of the photon-nucleus interaction for D and ^{4}He in the Δ resonance region, namely by the quasi-free production and the pion and proton rescattering. The extra cross section is compatible with the excitation of dibaryonic objects of masses of $Q_{NN\pi} = 2.16$ and $Q_{NN\pi} = 2.25$ GeV. More experimental data are needed, but every new result seems to confirm this assumption.

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