Measurement of π^0 Photoproduction in Deuterium near Threshold

P. Argan, G. Audit, A. Bloch, P. Bosted,[a] N. de Botton, J. L. Faure, C. Schuhl, G. Tamas, C. Tzara, and E. Vincent
Département de Physique Nucléaire, Centre d'Etudes Nucléaires Saclay, 91190 Gif-sur-Yvette, France

and

J. Deutsch, D. Favart, R. Prieels, and B. Van Oystaeyen
Institut de Physique Corpusculaire, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
(Received 27 April 1978)

π^0 photoproduction on deuterium has been measured in the region of 1 to 7 MeV above threshold, relative to the same reaction on hydrogen. The comparison of our results with available theoretical predictions shows the necessity to go beyond the impulse approximation.

Following our investigations of positive-pion photoproduction on light nuclei near threshold,[1] we have undertaken the study of neutral-pion photoproduction. Preliminary results have been reported which indicated the feasibility of such measurements.[2] We present here the results of an experiment performed on deuterium and hydrogen targets at energies ranging from 1 to 7 MeV above threshold.

In the case of positive-pion production, the dominant mechanism is the production of a π^+ on a nuclear proton with spin flip. The strong interaction of the pion with the nucleus modifies this picture only slightly.

For π^0 production two important differences must be stressed: (i) In the case of π^+ production, we measured as reference the elementary cross section (viz., $\gamma p \to n\pi^+$). Here, both the neutron and the proton contribute to the first-order amplitude, whereas we can only measure the cross section for the reaction $\gamma p \to p\pi^0$. (ii) Although the low-energy pion-nucleon scattering amplitudes are small, there is one term in the multiple-scattering expansion which cannot be neglected, namely the production of a virtual $\pi^\pm$ and its scattering with charge exchange on another nucleon. The importance of this effect, pointed out by Koch and Woloshyn,[3] is understood easily when one considers approximate expressions for the direct and rescattering amplitudes:

$$A_d \propto E_{0^+}{}^{\rm th}(\pi^0), \quad A_r \propto E_{0^+}{}^{\rm th}(\pi^\pm) a(\pi^\pm \to \pi^0)/\langle d \rangle.$$

The charge-exchange scattering amplitude $a(\pi^\pm \to \pi^0)$ is of the order of $\frac{1}{10}$ the average distance $\langle d \rangle$ between two nucleons. The threshold amplitude $E_{0^+}{}^{\rm th}$ for $\pi^\pm$ production is of the order of 10 times that for the π^0. Thus A_d and A_r are of the same order of magnitude. The next terms in the scattering expansion are unimportant, as they are depressed by the same factor $a/\langle d \rangle \sim 0.1$.

It is of particular interest to study π^0 photoproduction in the simplest nuclear systems for which we have a good knowledge of the wave functions. A comparative investigation of the process in light nuclei should give valuable information on the two important questions of the threshold π^0 photoproduction amplitudes on the nucleons and of the propagation of low-energy pions in the nuclear medium.

In this experiment we compare the π^0 photoproduction yields on deuterium and hydrogen at energies ranging from 1 to 7 MeV above threshold. We notice that the contribution of the breakup channel is negligible in our energy range, as inferred from the smallness of the ratio of the cross sections[1] $\sigma(\gamma d \to nn\pi^+)/\sigma(\gamma p \to n\pi^+)$.

The photon source is the bremsstrahlung beam produced in a 0.01-radiation-length tungsten converter hit by electrons of the Saclay linear accelerator. The momentum resolution of the electron beam is $\Delta p/p = 0.003$. The 15-μsec bursts are delivered at a rate of 1000/sec. A lead collimator defines a photon beam spot of 15 mm diameter at the target location. The photon intensity is measured by a Wilson-type quantameter. The cryogenic target consists of three identical cells (length, 11 cm; diameter, 3.8 cm), filled at 1 atm with liquid hydrogen (density 0.071 g cm^{-3}) and liquid deuterium (density 0.164 g cm^{-3}). The remaining cell is evacuated and used for control measurements. In order to avoid any contribution from π^0 production in the cell's steel windows, whose photoproduction threshold is lower than that on hydrogen and deuterium, a lead collimator masks them from the detectors.

The fact that the π^0 emitted near threshold have low velocity in the laboratory has helped the design of a simple and efficient detector. The photons from π^0 decay emitted almost back to back are converted in two 0.6-cm-thick lead foils placed at 90° on each side of the target. Each electron-positron pair is detected in an array of two Lucite detectors (4 cm thick) sandwiching one plastic scintillator (0.5 cm thick).

An event is defined by a coincidence of the six counters with a 30-nsec resolving time; the timing and the pulse height of each individual signal are measured. Losses of true events due to rather high individual counting rates are minimized with the help of an auxiliary 8-nsec coincidence circuit.

The analysis of the data is made off line. A rough estimate of the energy of the detected particles is obtained by adding the pulse heights measured in the four Čerenkov counters. Accidental events yield an energy spectrum that is peaked toward lower energies. Cuts on the energy spectra were thus made to improve the true-to-accidental ratio. We varied the coincidence width, and so we determined the contribution of the accidentals in the time window retained for the good events. In the worst case (hydrogen, 1 MeV above threshold), the true-to-accidental ratio was 4.

The background measured below threshold was assumed to be constant in the small energy range explored and was subtracted from the yields above threshold. They amounted to $\frac{1}{7}$ and $\frac{1}{5}$ of the yields obtained at 1 MeV above threshold for the hydrogen and the deuterium, respectively.

The experimental yields, normalized to one target nucleus and to the photon intensity, are presented in Table I. They are related to the π^0 photoproduction differential cross section $d\sigma/d\Omega$ by

$$A(E_0)=\int_{E_0}^{E_e}\int_{\Omega_d}B(E,E_e)\epsilon(E,\Omega)\,\frac{d\sigma}{d\Omega}\,d\Omega\,dE,$$

where $B(E,E_0)$ is the photon spectrum for an incident electron energy E_e, $\epsilon(E,\Omega)$ is the detection efficiency, E_0 is the threshold energy, and Ω_d is the solid angle viewed by the detection system.

The efficiency $\epsilon(E,\Omega)$ was computed by a Monte Carlo method. We took into account the exact geometry and kinematics and used a simple model to compute the pair production and its propagation in the counters. $\epsilon(E,\Omega)$ is known up to a factor C, the product of the efficiencies of the individual counters for a given cut in pulse height. C is common to both targets and is practically constant in our range of energy. The resulting efficiency ϵ varies with the π^0 emission angle by less than a few percent and so the detection system is sensitive to the total cross section only. To illustrate the variation of $\epsilon(E,\Omega)$ with π^0 energy, we present in Fig. 1 the case of a pion emission angle of 45° with respect to the photon direction.

We used the bremsstrahlung shape spectrum computed by Jabbur and Pratt.[4] The absolute energy scale was determined within ± 60 keV by measuring the yields for the reaction $\gamma p\to n\pi^+$ as described in Ref. 1.

The data on hydrogen are used to determine the constant C. Since the cross section for the reaction $\gamma p\to p\pi^0$ is not known experimentally in the energy range explored in the present work, we have chosen to use a theoretical proton cross section, common to Refs. 5 and 6. The fit to the

TABLE I. Experimental yield $A(E_e)=\int_{E_0}^{E_e}\int_{\Omega_d}B(E,E_e)\epsilon(E,\Omega)(d\sigma/d\Omega)d\Omega\,dE$ in microbarns, normalized to one target nucleus and one equivalent quantum, for different values of the bremsstrahlung endpoint energy E_e above threshold E_0.

Hydrogen E_e-E_0 (MeV)	Hydrogen 10^6A_H	Deuterium E_e-E_0 (MeV)	Deuterium 10^6A_D
1.04	0.16 ± 0.06	0.88	0.40 ± 0.07
2.04	0.61 ± 0.11	1.88	1.16 ± 0.11
3.04	0.92 ± 0.13	2.88	2.64 ± 0.26
4.04	1.94 ± 0.27	4.88	6.66 ± 0.37
6.04	4.29 ± 0.36	5.88	10.62 ± 0.55
		7.38	16.48 ± 1.50

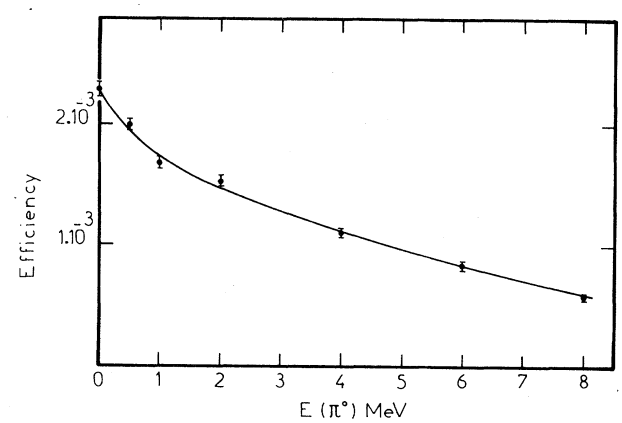

FIG. 1. The π^0 telescope efficiency ϵ as a function of the π^0 energy for pions emitted at 45° with respect to the photon beam.

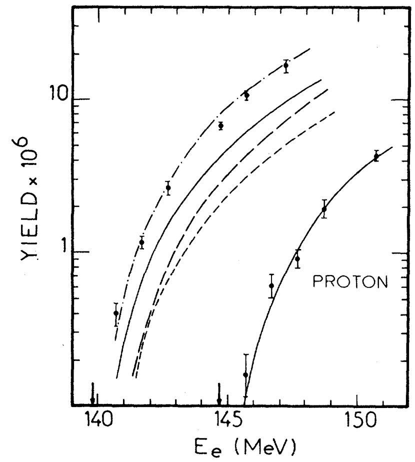

FIG. 2. The measured photoproduction yields as a function of the bremsstrahlung endpoint energy E_e compared to theoretical estimates for deuterium without rescattering (long dashes, Ref. 6, and short dashes, Ref. 5) and including rescattering (dash-dotted line, Ref. 6, and solid line, Ref. 5). These two theoretical estimates use the same proton cross section; the corresponding yield has been adjusted to the hydrogen data. Arrows indicate the threshold energies. The yields are given in microbarns per equivalent quantum.

proton experimental yields is satisfactory ($\chi^2/n = 0.9$); see Fig. 2. It gives $C = 0.53$, corresponding to an average efficiency of the individual counters of $C^{1/6} = 0.9$, a plausible value. This efficiency is used to compute the theoretical yields displayed in Fig. 2 from the deuterium theoretical cross sections.[5,6] The yields obtained by neglecting the rescattering amplitude are definitely lower than the experimental ones. With the inclusion of the rescattering amplitude, one obtains significant improvement. The yield based on the calculation of Ref. 6 is in perfect agreement with the experimental data, whereas the one based on the theory of Ref. 5 is 2 times smaller. The reason for this difference can be traced back to the use of different deuteron wave functions. The Hulthén wave function used in Ref. 6 is too dense at the origin and unduly enhances the rescattering amplitude, producing the apparent agreement with experiment. In Ref. 5 the authors have indeed verified that if they use the Hulthén wave function instead of their more realistic one they obtain agreement with our data.

However, the treatment of the virtual pion and nucleon dynamics is not unambiguous; different choices for the off-mass-shell behavior of the participating particles modify the magnitude of the predicted cross section.

One should note that the π^0 photoproduction and scattering amplitudes could be influenced, in the threshold region, by the opening of the charged-pion channels. Such an effect has not been investigated up to now.

We have investigated the influence of a variation of the elementary amplitudes on the proton and the deuteron yields. It appears that our proton measurements favor values of $E_{0^+}(p\pi^0)$ compatible with the prediction of the partial conservation of axial-vector current,[7] namely $-0.0025 m_\pi^{-1}$. Using the rescattering amplitude of Ref. 5, we obtained agreement with the experimental deuterium yields only with an $E_{0^+}(n\pi^0)$ amplitude significantly smaller than the one predicted by the partial conservation of axial-vector current.

We wish to thank P. Stoler and J. Blomqvist for participating to the initial stage of the experiment and M. Ericson for fruitful discussions. We acknowledge the cooperation of the Saclay linear accelerator crew and the technical assistance of G. Ardiot, J. Béchade, M. Berger, and J. Mommejat. One of us (D.F.) acknowledges an appointment as chercheur of the Fédération Nationale Research Scientifique, Brussels, Belgium.

[a] Permanent address: Massachusetts Institute of Technology, Cambridge, Mass. 02139.

[1] G. Audit *et al.*, Phys. Rev. C 15, 1415 (1977), and 16, 1517 (1977).

[2] C. Tzara, in *Meson-Nuclear Physics—1976*, edited by P. D. Barnes, R. A. Eisenstein, and L. S. Kisslinger, AIP Conference Proceedings No. 33 (American Institute of Physics, New York, 1976), p. 566.

[3] J. H. Koch and R. M. Woloshyn, Phys. Lett. 60B, 221 (1976).

[4] R. J. Jabbur and R. H. Pratt, Phys. Rev. 129, 184 (1963), footnote 18.

[5] P. Bosted and J. M. Laget, Nucl. Phys. A296, 413 (1978).

[6] J. H. Koch and R. M. Woloshyn, Phys. Rev. C 16, 1968 (1977).

[7] P. de Baenst, Nucl. Phys. B24, 633 (1970).