Precise Measurement of Neutral-Pion Photoproduction on the Proton near Threshold

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An absolute measurement of π^0 photoproduction on the proton has been carried out in the threshold region (from 144.7 to 173 MeV) by use of tagged annihilation photons. The measured cross sections, differential in the recoiling-proton energy, are used to perform a multipole analysis which gives a value $(-0.5\pm0.3)\times10^{-3}/m_{\pi^+}$ for the dipole amplitude E_{0^+}, in disagreement with low-energy-theorem predictions. Total cross sections and coefficients of the π^0 angular distribution are presented.

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Pion photoproduction amplitudes at threshold are fundamental quantities of s-wave pion-nucleon physics. Low-energy theorems for soft photons and pions together with the PCAC (partial conservation of axial-vector current) hypothesis allow the expression of the pion photoproduction amplitude in terms of the pion-nucleon coupling constant and the static properties of the nucleon.[1] Charged-pion amplitudes are predicted up to first order in a m_π/M (the ratio of pion to nucleon mass) expansion. The corresponding experimental values are in good agreement with this approximation. From this comparison one can set limits for terms of higher order in the expansion. These terms are essentially dispersive corrections involving N^* resonances and vector-meson exchange.

In the case of neutral-pion photoproduction, only the proton amplitude can be directly measured. Low-energy theorems show that this amplitude vanishes with m_π/M and they predict contributions up to second order. Within this framework, the electric dipole amplitude $E_{0^+}(p\pi^0)$ is[2] $-2.4\times10^{-3}/m_{\pi^+}$ (these units will be used throughout the text). The mass difference of neutral and charged pions or nucleons induces, through the properties of unitarity and analyticity of the S matrix, an anomaly ("cusp") in the variation of $E_{0^+}(p\pi^0)$ with energy.[3,4] The coupling of π^0p and π^+n channels (i) produces an imaginary part in the $E_{0^+}(p\pi^0)$ amplitude above π^+ threshold (151.4 MeV), and (ii) enhances the real part of $E_{0^+}(p\pi^0)$, as compared to its value when mass differences within multiplets are neglected, in the region between the π^0 threshold (144.7 MeV) and the π^+ threshold. It is the value of this ideal isospin-symmetric amplitude at threshold which we will quote as $E_{0^+}(p\pi^0)$ and which is to be compared to the low-energy-theorem predictions.

Until now there has been no reliable experimental information on the threshold cross section, since all existing measurements have been performed with use of bremsstrahlung photon spectra with end-point energies exceeding the reaction threshold by more than 15 MeV. Extraction of the slope of the cross section at threshold from these experiments requires averaging and extrapolation procedures with uncertainties which are only partially accounted for in the quoted error. The current experimental value is $E_{0^+}(p\pi^0)=-1.8\pm0.6$,[5] in agreement with theoretical predictions.

We report here an absolute measurement of neutral-pion photoproduction on the proton using a tagged annihilation photon beam and covering the energy region from threshold up to 173 MeV. The experiment involved the detection, in coincidence with the tagging photon, of the two π^0-decay photons and of the recoiling proton. From the measured cross sections, differential in the proton energy, an analysis was performed in terms of angular distribution coefficients and of multipolar amplitudes. Total cross sections were obtained from these data.

The experiment utilized photons from the tagged annihilation facility[6] at the Saclay linear electron accelerator ALS. Accelerated positrons annihilate on a 40-mg/cm^2 LiH radiator and the low-energy annihilation photon is used to tag the high-energy one. The tagging detector provided a 1-MeV energy resolution for the tagged photon. The size of the tagging detector defined the total 8-MeV energy width of the photon beam. The photon flux, mainly limited by counting rates in the target, was 8000 sec^{-1}.

The recoiling-proton energy was measured through the scintillation light output in the active target, a stack of twenty 5-mm-thick scintillators viewed by individual photomultipliers. The carbon content of the target is an important source of π^0 because of the lower threshold energy (135.8 MeV) and because of the coherent character of the production reaction which leaves the carbon nucleus in its ground state. However, the light output of a recoiling carbon is much smaller than the scintillation of the lowest-energy recoiling protons, providing a straightforward method of discrimination between the two processes. Only incoherent π^0 photoproduction on carbon with proton emission could be misleading. The threshold of this process is 7 MeV above the proton π^0 production threshold; its cross section has been estimated[7] and found to be only a few percent of the coherent production in our energy range, but it is not necessarily negligible compared to that on the free proton. However, because of the difference in threshold energies, the proton spectrum observed for incoherent carbon production has its tip much lower than the maximum proton energy observed in photoproduction on the proton. Consequently the detection threshold of the protons, which was set at 5 MeV, was much more effective for the incoherent reaction on carbon than for the investigated process for which less than 10% of the protons were eliminated. Contamination of the proton spectra by inelastic photoproduction on carbon was evaluated by our fitting the experimental spectra with a linear combination of the theoretical spectra[7] from the two competing reactions. It was shown to be around 2% at 160 MeV and not to exceed 15% at 170 MeV.

Calibration of the proton recoil energy was made on line with use of the one-electron and two-electron peaks associated with electromagnetic showers in the target. In order to deduce the recoiling-proton energy from the scintillation-light output in the target scintillator an ancillary measurement was performed which used incident-momentum–analyzed low-energy protons (in the range 2–20 MeV) and 110-MeV electrons.

Neutral pions were detected through their two-photon decay in a cylindrical lead-glass Cherenkov detector surrounding the target and covering a $0.95\times4\pi$ solid angle. The detector was divided into twelve pieces of a size such that a π^0 decay in the energy region that we considered could not fire two adjacent blocks. The lead-glass thickness was 6 radiation lengths (r.l.). The inner surface of the detector was covered with twelve 5-mm-thick scintillators which vetoed charged particles, mostly components of the electromagnetic shower initiated by the photon beam in the target.

Incoming photons were counted by means of a 16-r.l.-thick lead-glass block, downstream from the target, set in coincidence with the tagging detector. The efficiency of this detector was larger than 99% for photons of energy 140 to 180 MeV as shown by a simulation performed with the EGS code.[8] However, because of the high instantaneous counting rates in both counters corrections were made to account for accidentals and counting losses; this resulted in uncertainties of $\pm3.5\%$ in the absolute number of incident photons on the reaction target.

Veto counters set in the beam line were used to eliminate stray particles and electromagnetic shower events.

The various types of triggers we considered were as follows: (i) "π^0" characterized by a coincidence between the tagging detector and a signal corresponding to an energy deposited in the π^0 detector exceeding 40 MeV. Subsequent analysis of the target and of the pattern of the twelve lead-glass blocks allowed identification of the events as coherent π^0 photoproduction on carbon, π^0 photoproduction on the proton, or Compton events. (ii) "Photons" characterized by a coincidence between the tagging detector and the photon detector. (iii) Random triggers to determine the pedestals of amplitude coders and electronic efficiencies.

The detection efficiency for π^0 events was calculated by a simulation which used (i) the EGS code for the π^0-decay-photon detection part and (ii) tabulated energy losses and our determination of the quenching function for the recoiling proton in the target scintillators. The simulation includes the exact geometry of our setup and a π^0 photoproduction cross section given in terms of s- and p-wave multipoles. The amplitude calibration and thresholds for the individual Cherenkov counters and the light-collection resolution were determined in order to account for the experimental spectra and the Cherenkov multiplicities for good π^0 events. The global detection efficiency (typically 0.55) is essentially determined by the setup geometry and by the kinematics of the reaction and of the π^0 decay. Cuts in the pulse-height spectra of the Cherenkov counters and of the active target scintillators represent respectively 5% and 8% of the counts. Systematic uncertainties affect only this 13% in efficiency and are therefore negligible when compared to the precision of the final result.

An important feature of the experiment was the calibration of the incident-photon-energy scale using the highly accurate data on π^0 photoproduction on carbon.[9] Using the variation of the cross section with energy in the vicinity of threshold, we were able to define the absolute threshold of the reaction from the measurement with a central photon energy of 136 MeV. We observed a shift of 0.7 ± 0.2 MeV relative to the photon energy deduced from the positron's nominal incident momentum. This shift is compatible with the uncertainties in the positioning of the beam transport magnets and of the tagging-system detectors.

In order to present statistically significant experimental results, the events were summed over the entire photon energy spectrum for each of the twelve runs corresponding to different photon-energy settings. However, we used the 1-MeV resolution capability of the system to select the events initiated by photons whose energy was larger than the reaction threshold. Low-positron-intensity runs were performed to determine accurately the energy spectrum of the photons incident on the target. They provide a precise definition of the average incident photon energy.

Our results consist of cross sections, differential in the proton energy. In Fig. 1 we show the proton energy distribution spectra obtained at $E_\gamma=147.5$ and 152.4 MeV. In Table I we have listed the total cross sections as functions of incident photon energy. In Fig. 2 we compare our total-cross-section values to the existing ones and to calculated curves which use multipole amplitudes determined at higher energy. The calculated cross sections take into account the cusp effect, by use of general principles of S-matrix unitarity and analyticity and of time-reversal invariance.[15] Below 150 MeV the data are

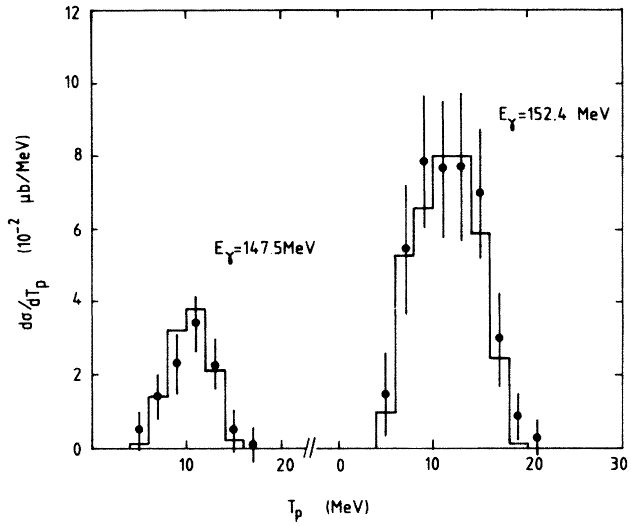

FIG. 1. The π^0-photoproduction differential cross section as a function of the recoiling-proton energy for the $E_\gamma=147.5$- and 147.6-MeV and for the $E_\gamma=152.4$-MeV runs. The histograms correspond to the fit discussed in the text.

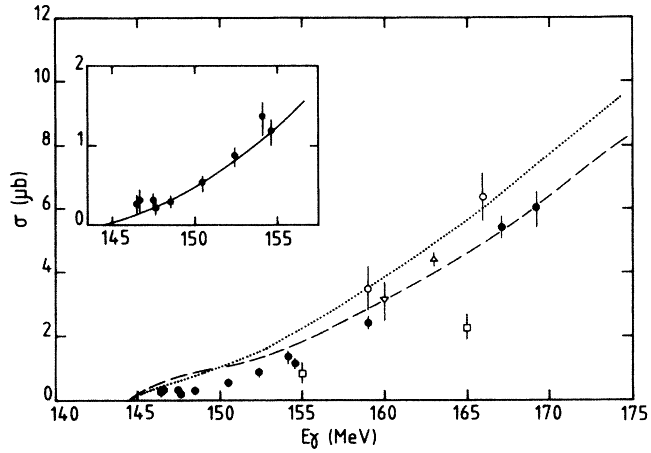

FIG. 2. The π^0-photoproduction cross section on the proton as a function of the average photon energy. Experimental points: closed circles, this work; squares, Koester (Ref. 10); inverted triangles, Vasilkov (Ref. 11); triangles, Govorkov (Ref. 12); open circles, Hitzeroth (Ref. 13). The dotted and dashed curves are calculated cross sections which use mutlipoles derived, respectively, from Pfeil and Schwela (Ref. 14), and from Laget (Ref. 4). The inset is an enlargement of the region 10 MeV above the threshold; the solid line is the total cross section corresponding to the multipole determination which fits the differential-cross-section values.

much lower than these predictions, which use values of the multipole amplitude E_{0^+} at threshold of -2.6[4] and -1.9.[14] This strongly suggests a much smaller value for the dipole amplitude.

Using a parametrization of the differential cross section in terms of the leading multipoles E_{0^+}, M_{1^+}, and M_{1^-}, we extracted their amplitudes from the subset of our data corresponding to average photon-energy excess above threshold of less than 10 MeV. M_{1^+} and M_{1^-} are almost real and they are supposed to keep their threshold theoretical behavior (proportional to the product of pion and photon center-of-mass momenta qk) in this photon energy range. Folding the differential cross section with the measured photon spectra, we fitted the data of the nine lowest energy runs with these three parameters. We obtained a fit with $\chi^2=52$ for 69 degrees of freedom, yielding the following values for the multipole amplitudes:

$$E_{0^+}=(-0.46\pm0.24)\times10^{-3}/m_{\pi^+},$$

$$M_{1^+}=(8.0\pm0.3)qk\times10^{-3}/m_{\pi^+}^3,$$

$$M_{1^-}=(-2.0\pm1.5)qk\times10^{-3}/m_{\pi^+}^3.$$

The data are only marginally sensitive to the M_{1^-} amplitude as is apparent from its large uncertainty. One should note, however, the consistency of the determinations of the magnetic-dipole amplitudes with current values at higher energy.[4,14] The correlation between the different multipoles is moderate. Inclusion of quadratic

TABLE I. The proton π^0-photoproduction cross section in microbarns and the c.m. pion angular-differential-cross-section coefficients in microbarns per steradian as functions of the incident average photon energy E_γ in megaelectronvolts.

E_γ	σ	$\Delta\sigma$	A	ΔA	B	ΔB	C	ΔC
146.5	0.25	0.12	0.000	0.013	−0.004	0.012	0.033	0.014
146.6	0.30	0.14	0.001	0.008	−0.015	0.009	0.053	0.011
147.5	0.30	0.09	0.003	0.007	−0.024	0.011	0.049	0.015
147.6	0.20	0.08	0.002	0.010	−0.013	0.006	0.031	0.024
148.5	0.29	0.07	0.015	0.014	−0.025	0.010	0.022	0.035
150.5	0.52	0.08	0.044	0.010	−0.020	0.011	−0.007	0.027
152.4	0.86	0.12	0.064	0.014	−0.021	0.018	0.018	0.040
154.1	1.34	0.20	0.111	0.029	−0.036	0.033	−0.035	0.078
154.6	1.16	0.16	0.113	0.013	−0.049	0.011	−0.064	0.070
159.0	2.44	0.20	0.203	0.028	−0.031	0.038	−0.008	0.077
167.1	5.42	0.34	0.370	0.046	0.005	0.064	0.160	0.128
169.2	6.01	0.58	0.361	0.076	−0.105	0.111	0.295	0.211

terms in qk in the magnetic-multipole parametrization and analysis of different subsets of the data influence slightly the E_{0^+} value. With these variations taken into account our final value is

$$E_{0^+} = (-0.5 \pm 0.3) \times 10^{-3}/m_{\pi^+}.$$

In an alternative analysis we decomposed the proton-energy–differential cross section in terms of the parameters describing the pion angular distribution in the center-of-mass frame. Assuming only s- and p-wave contributions we fitted the data for each individual run with the expression $A + B\cos\theta + C\cos^2\theta$, with the constraint that the cross section be positive. The determinations of the parameters A, B, and C are given in Table I with their uncertainties. The sign of B is negative for all values of energy, hence imposing opposite signs for E_{0^+} and M_{1^+}.

Agreement with previous higher-energy measurements[10–13] of the process is satisfactory considering moreover the systematic uncertainties discussed above which are not included in the errors of the published cross-section values. Extrapolation procedures used in these experiments to get the values of the multipoles at threshold are evidently unreliable since they predict cross sections more than twice as large as the values that we have measured in the photon energy region up to 155 MeV. This confirms the necessity of extracting the threshold values of multipoles from low-energy measurements.

Our multipole set does not disagree with our previously measured shape of the hydrogen total cross section.[16] Clearly our E_{0^+} result casts some doubt on the models used in the analysis of π^0 photoproduction on light nuclei.

The striking departure of the experimental value of E_{0^+} from the low-energy-theorem predictions could indicate important dispersive corrections affecting the higher-order terms in the m_π/M development. Indeed, Benfatto *et al.*,[17] in an evaluation of the contributions of baryonic-resonance excitation to the threshold amplitudes, find a value $E_{0^+} = -0.7 \pm 0.5$, close to our result.

Some implications of this unexpected situation could be crosschecked. For instance, the value of the multipole $E_{0^+}(n\pi^0)$ at threshold, which can be deduced from the isospin-symmetry relation linking the four photoproduction channels, is, by use of the best experimental data, 2.0 ± 0.5. Such a large difference between π^0 photoproduction cross sections on the neutron and on the proton in the vicinity of threshold should show up in a comparison of π^0 production on the mirror nuclei ^{3}He and ^{3}H.

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