ELECTROPRODUCTION OF NEUTRAL PIONS AT THRESHOLD AND IN THE DELTA RESONANCE REGION*

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The history of π^0 photoproduction near threshold on the proton and recent results of π^0 electroproduction are discussed, including a comparison with recent calculations in Chiral Perturbation Theory. Then an experiment on coherent π^0 production on ^{4}He in the Δ region, in which Δ · propagation through a nucleus and a two-body mechanism of pion production will be studied, is described. A special detector is developed for the detection of the recoiling ^{4}He nuclei.

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1. Introduction

The pion plays a central role in strong-interaction physics. First of all, it is the particle that mediates (part of) the strong interaction between nucleons. Secondly, many nucleon resonances, for instance the delta, have a large width for decay into a pion plus a nucleon. Finally, because of the low mass of the pion the production of a pion is the lowest-energy reaction that produces an extra hadron. For these reasons the study of pion production, both on nucleons and nuclei, is of fundamental importance.

If one wants to study the production process itself, one likes to start with investigating the production on a nucleon and use a well known interaction like the electromagnetic interaction, i.e., one should study pion production with real and virtual (γ_v) photons on the proton and neutron and thus determine the elementary amplitudes. The study of these processes near the threshold for the reaction has the special feature that effective theories, like

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Chiral Perturbation Theory (ChPT), that represent the low-energy limit of quantum chromodynamics, can be used to describe the process. The reason behind this is that the pion as an (almost) Goldstone boson is related to spontaneous chiral-symmetry breaking. Especially π^0 production provides a very sensitive test of these theories, since the first order term in the production amplitude is zero because of the zero charge of the neutral pion.

On the meson-nucleon level, which is more apt for applications also in heavier nuclei, the production is described in a Hamiltonian model, which contains a $\gamma\pi N$ production operator and a πN (or πA) interaction Hamiltonian. In this way $e.g.$the final-state interaction in the $^1\mathrm{H}(\gamma_v, \pi^0)\mathrm{p}$ reaction yields information on $\pi^0 + \mathrm{p}$ scattering and, through the two-step process $^1\mathrm{H}(\gamma_v, \pi^+)(\pi^+, \pi^0)\mathrm{p}$, on the (π^+, π^0) process at very low pion energies.

Another interesting regime is pion production on a nucleus in the delta resonance region. This process depends, apart from the elementary production amplitude and the nuclear structure, on the propagation and decay of the Δ in a nuclear medium, as described, for instance, by the Δ-hole model. Also here π^0 production is the most crucial test, since neutral pion production in the delta region proceeds almost completely through Δ formation and decay, in contrast to charged-pion production, where Born terms give a large contribution.

After a short survey of π^0 production on a nucleon and the relevant theories, the history and most recent results of π^0 photoproduction on the proton near threshold are described in Section 2.1, while the results of the new electroproduction experiments, including comparisons with recent ChPT calculations, are discussed in Section 2.2. In Section 3 an experiment to measure coherent π^0 production on $^4\mathrm{He}$ is described, which aims at studying Δ propagation in $^4\mathrm{He}$ and a possible two-body mechanism of pion production in a nucleus. The special detector that is developed to measure the recoiling $^4\mathrm{He}$ nuclei instead of the π^0-particles is also described. A summary and outlook is given in Section 4.

2. π^0 production on the nucleon near threshold

At threshold the reaction is described by the pion s-wave multipoles E_{0+} and L_{0+} only. Away from threshold the p-wave multipoles E_{1+}, M_{1+}, M_{1-}, L_{1+} and L_{1-} start contributing. The L multipoles contribute only to electroproduction. The notation $X_{l\pm}$ is used here, in which X stands for the type of photon (E or M in photoproduction; E, M or L in electroproduction), l stands for the pion angular momentum with respect to the nucleon in the final state, and $\pm$ denotes the total angular momentum $j = l \pm \frac{1}{2}$ in the final state.

As mentioned already in the introduction there are several theoretical predictions for E_{0+} and L_{0+}, and also for the p- multipoles, which can be compared to data on pion production at low energy.

Chiral perturbation theory (ChPT) [1] starts with an effective πN Lagrangian, in which the effect of chiral symmetry breaking is treated in a perturbative fashion. It makes a prediction for the values of the multipoles by calculating all the contributing diagrams up to a certain order in q, where q is any external momentum or the pion mass. Since it is an effective theory ChPT contains some free parameters. These can be either estimated from some model, or they can be determined from a set of experimental data, notably pion and nucleon properties and πN scattering data and, for the present case, from photo- or electroproduction near threshold.

In the past data have been compared to what are now called 'old' low-energy theorems (LETs) [2, 3]. These predict the values of the E_{0+} and L_{0+} multipoles at threshold up to some order in μ, where $\mu = m_\pi/m_p$, with m_π the mass of the pion and m_p the mass of the proton, by using gauge invariance, partial conservation of axial current, crossing symmetry and assuming that there are no non-analytic terms in the invarant amplitudes. Originally the LET was derived for photoproduction only. The formalism has been extended by Scherer and Koch [3] to the case of electroproduction. More recently ChPT calculations have shown that an important term of order μ^2 has to be included in the 'old' LET and that the series is slowly converging [4]. Consequently comparisons with LET values (whichever), at least for the s-wave multipoles, make little sense anymore.

Furthermore, there are models based on an effective πN Lagrangian, in which an elementary production amplitude for the production of a pion is calculated by evaluating the nucleon and delta-isobar Born terms. Some models also include the coupling of the photon to a vector meson. The main differences between the various calculations arise from the model being relativistic or non-relativistic and from the treatment of the Δ and vector-meson-exchange terms. Rescattering can be incorporated by either using Watson's theorem [5], or by calculating the rescattering with a specific πN potential. Examples of this approach are the models of Nozawa, Blankleider and Lee [6], Davidson [7], and Blaazer [8].

2.1. π^0 photoproduction on the proton near threshold

The E_{0+} multipole near threshold has first been measured in photoproduction experiments at Saclay and Mainz [9, 10]. These experiments induced a lot of excitement and discussion, because initially the extracted value for E_{0+} at threshold was not in agreement with the ('old') LET prediction. The discussions revolved around the question how to account for the

$\gamma p \rightarrow \pi^+ n \rightarrow \pi^0 p$ contribution, since the value of the E_{0+} multipole varied strongly as a function of the invariant energy W, which is attributed to the influence of the charge-exchange process. The first ideas were that because of this one has to compare the LET prediction to the E_{0+} value measured at the threshold for the $^1H(\gamma, \pi^+)n$ reaction, which lies 5.9 MeV above the one for π^0 production. After some time and many discussions there was consensus that the LET for π^0 production has to be applied at the π^0 threshold [11], and subsequent re-analyses of the data [12–14] showed a good agreement between the extracted value of the E_{0+} multipole at threshold and the prediction obtained from the LET. However, as mentioned, ChPT has shown that the value of the 'old' LET was incorrect.

Furthermore new data obtained at Mainz [15] and Saskatoon [16] yield a smaller value of E_{0+} at threshold. The value was extracted from measurements of the total cross section and from the measured pion angular distribution. As an example the total cross section data from the SAL measurement and the determined values of the real part of E_{0+} are shown in Fig. 1.
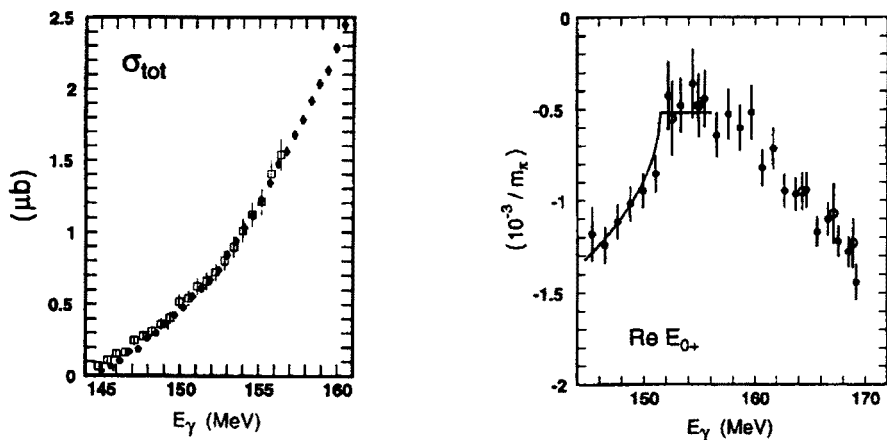

Fig. 1. Total cross section and value of E_{0+} from the SAL measurements.

The total cross section data from the new measurements agree with each other near threshold, but they are lower than the older data. At higher energies the SAL data are higher than the new Mainz data and resemble more the old Mainz data. The new values for E_{0+} are in close agreement with recent ChPT estimates [4], which yield a value of $-3.45(1 - 1.26 + 0.55 + ...) \approx -1.0$ in the canonical units $10^{-3}/M_{\pi+}$ (the different terms are due to different orders in μ).

2.2. π^0 electroproduction on the proton near threshold

There are several reasons why one would like to investigate also π^0 electroproduction on the proton near threshold. Firstly, one can study the L_{0+} multipole, which is absent in photoproduction. It will also be interesting to see how this multipole is influenced by the charge-exchange channel. Secondly, one can investigate the Q^2 dependence of *e.g.* the E_{0+} multipole. Finally, four structure functions (in the case of no polarisation) contribute to electroproduction instead of only one in photoproduction. By separating (some of) these structure functions one can enhance the sensitivity to the different contributing multipoles. Hence the study of electroproduction enables a much more detailed comparison with the results from various theoretical models.

The first π^0 electroproduction experiment near threshold was performed at NIKHEF with the 1% duty factor beam available at that time [17]. In that experiment the quantity $a_0 = |E_{0+}|^2 + \epsilon_L|L_{0+}|^2$, which determines the total ^{1}H(e,e'π)p cross section at threshold, was measured close to threshold for values of Q^2 of 0.05 and 0.10 (GeV/c)^2. The factor ϵ_L is given by $\epsilon_L = \epsilon Q^2/\omega^{*2}$, where ϵ is the virtual-photon polarisation parameter and ω is the energy of the virtual photon, while the asterisk indicates that it is the value in the center of mass frame. With some reasonable assumptions the value of the L_{0+} multipole was extracted and extrapolated to $Q^2 = 0$. The resulting value was in agreement with the LET prediction from Ref. [3]. A calculation of the Q^2 dependence of a_0 within chiral perturbation theory [18] showed a good agreement with the data.

A much more detailed experiment [19, 20] was performed at NIKHEF in 1994 with the high dutyfactor beam from the Pulse Stretcher ring AmPS [21]. The goal of that experiment was to study the E_{0+} and L_{0+} multipoles in the reaction ^{1}H(e,e'π)p separately, including their energy dependence. This was done by measuring the angular distribution for π^0 production for values of the invariant energy W from 1 to 14 MeV above the threshold, thus covering a range of several MeV around the π^+ threshold. The detection of the π^0 was avoided by measuring the recoil proton instead. The electron energy was 525 MeV, the current 10 μA, and the duty factor about 30%. The target was a cryogenic H$_2$ target operated at 35 K and 1.5 MPa, just above the critical point. There the density varies strongly with both the pressure and temperature. The chosen density of 22 mg/cm^3 was a compromise between count rate and the amount of energy loss and angle straggling in the target gas. With an effective target length of 2.5 cm, as viewed by the QDD spectrometer, which was the limiting one, the luminosity was $2 \times 10^{37} e^-$ at/sec.
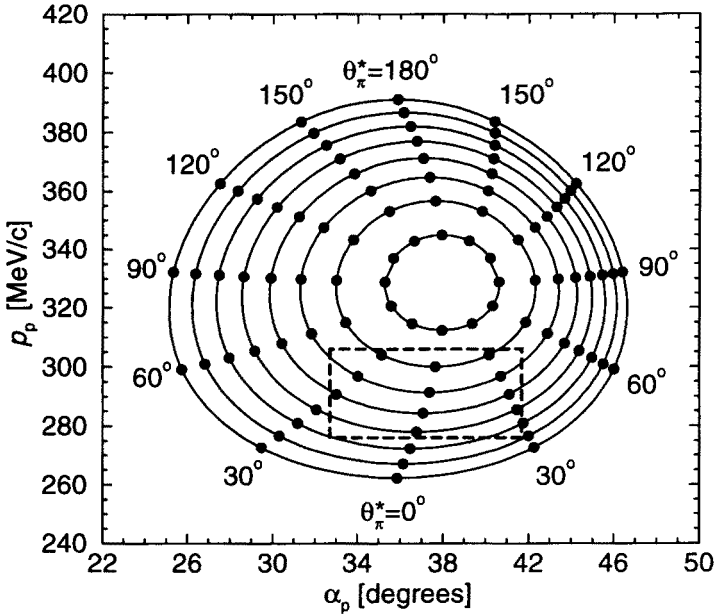
Fig. 2. Proton momentum p_p versus angle with the electron beam, α_p, in the lab frame, for protons emitted in the scattering plane. The curves are for values of the invariant energy W of 1, 3, 5, 7, 9, 11, 13, and 15 MeV above threshold. The numbers indicate the polar angle of the pion in the CM frame. The right-hand part of the curves corresponds to $\phi_\pi^* = 0°$ and the left-hand part to $\phi_\pi^* = 180°$. The dashed rectangle indicates the momentum and angular acceptance of the QDQ spectrometer in the $\theta_\pi^* = 0°$ kinematic (see text).

The scattered electrons, which determine the values of Q^2 and W, were detected in the QDD spectrometer. The resolution in W is estimated to be better than 0.3 MeV. The protons, which are emitted in a cone around q, were detected in the QDQ spectrometer. For every value of W (and a given Q^2) there is a relation between the direction of the proton (which is directly related to the direction $(\theta_\pi^*, \phi_\pi^*)$ of the emitted pion) and its momentum, see Fig. 2. Data were taken in four kinematics with central values at $W = 6$ MeV above threshold for θ_π^* of $0°$, $90°$ (for both $\phi_\pi^* = 0°$ and $180°$) and $180°$. Since the momentum bite of the QDQ spectrometer is $\pm 5\%$ and its opening angle $\pm 4°$, globally the region $W = 2 - 12$ MeV above threshold and $\theta_\pi^* = 0° - 180°$ was covered, with data around $\theta_\pi^* = 90°$ for both $\phi_\pi^* = 0°$ and $180°$.

In order to reconstruct θ_π^* (and ϕ_π^*) from the data the transformation from the wire chamber information in the focal plane of the spectrometer to the target vector has to be known accurately, and this for an extended target. This transformation has been carefully calibrated in the past with so-called sieve-slit measurements [22, 19]. As a check on the used calibration some sieve-slit data were taken during the π^0 measurements. Also the kinematically overcomplete ^{1}H(e,e'p) reaction was used as a check on the reconstruction of the target vectors and on the corrections for energy loss in the target. At the same time the coincidence efficiency was determined with this reaction to be $99 \pm 1\%$. Data were collected for different values of the integrated charge for the four kinematics such that the absolute statistical errors in the cross sections would be about the same.

For the determination of the cross section the detection volume $dE_{e'}d\Omega_{e'}d\Omega_\pi^*$ has to be known. Because one is near threshold and because the effective θ_π^* acceptance of the QDQ spectrometer strongly depends on the value of W, this detection volume is a strongly non-linear function of $e.g. E_{e'}$ and $\Omega_{e'}$. Hence it was calculated in a Monte Carlo program.

The coincidence cross section can be written as [23]

$$\frac{d^5\sigma}{dE_{e'}d\Omega_{e'}d\Omega_\pi^*} = \Gamma_v \frac{d\sigma}{d\Omega_\pi^*}, \tag{1}$$

where Γ_v is the virtual photon flux factor.

Assuming only s- and p-waves for the pion (which is a good approximation close to threshold) the expression for the cross section can be written as [14]:

$$\begin{aligned}\frac{d\sigma}{d\Omega_\pi^*} = \frac{p_\pi^*}{q_L}\frac{W}{m_p}\{&A + B\cos\theta_\pi^* + C\sin\theta_\pi^*\cos\phi_\pi^* \\ &+ D\cos^2\theta_\pi^* + E\sin^2\theta_\pi^*\cos(2\phi_\pi^*) \\ &+ F\sin\theta_\pi^*\cos\theta_\pi^*\cos\phi_\pi^*\},\end{aligned} \tag{2}$$

where ϕ is the angle between the (e, e') and (q, p_π) planes and the coefficients A, B, C, D, E, and F are combinations of s- and p-wave multipoles, which depend on Q^2 and W. The coefficients can be written as

$$\begin{aligned} A &= \epsilon_L|L_{0+}|^2 + |E_{0+}|^2 + \tfrac{1}{2}|3E_{1+} - M_a|^2 + \tfrac{1}{2}|M_b|^2 \\ B &= 2\text{Re}\{E_{0+}^*(3E_{1+} + M_a)\} \\ C &= -\sqrt{2\epsilon_L(\epsilon + 1)}\,\text{Re}\{L_{0+}^*(3E_{1+} - M_a)\} \\ D &= |3E_{1+} + M_a|^2 - \tfrac{1}{2}|M_b|^2 - \tfrac{1}{2}|3E_{1+} - M_a|^2 \\ E &= 3\epsilon(\tfrac{3}{2}|E_{1+}|^2 - \tfrac{1}{2}|M_{1+}|^2 - \text{Re}\{E_{1+}^*M_a + M_{1+}^*M_{1-}\}) \\ F &= 0, \end{aligned} \tag{3}$$

with M_a and M_b combinations of M_{1+} and M_{1-}:

$$M_a = M_{1+} - M_{1-}$$
$$M_b = 2M_{1+} + M_{1-}. \tag{4}$$

In these formula's terms containing the L_{1-} and L_{1+} multipoles have been neglected, since in all models they are calculated to be small.

In every W bin the θ_π^*,ϕ_π^*-dependent cross section was fitted with the function of Eq. 2, with the coefficients A, B, C, D and E as free parameters. From Eq. 2 it can be seen that the value of the coefficient B is globally determined by comparing the cross sections at $\theta_\pi^* = 0°$ and 180°. Similarly the value of C is given by the difference between the cross sections at $\phi_\pi^* = 0°$ and 180°. The values of A, B and C as a function of ΔW are shown in Fig. 3. The coefficient A is a combination of the squares of the s-wave multipoles and the squares of combinations of p-wave multipoles. Therefore, the value of A can be parametrised as $A = a_0 + bp_\pi^{*2}$, ignoring a possible energy dependence of the multipoles. The result is indicated in Fig. 3 by the solid curve.
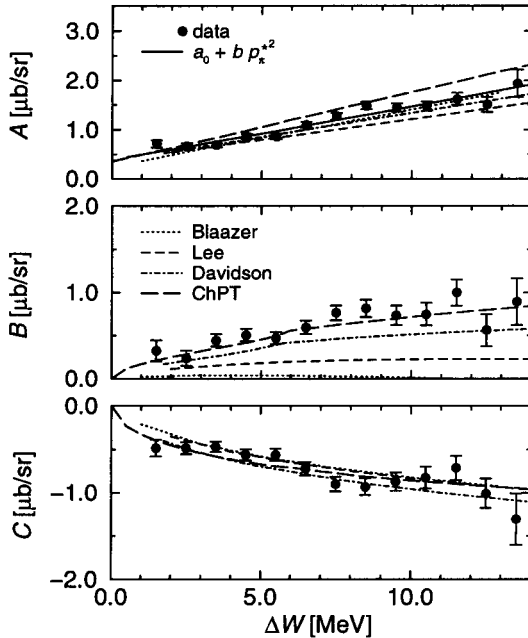

Fig. 3. Coefficients A, B and C, obtained from fitting Eq. (2) to the measured cross sections.

The extracted values of A, B and C are compared to the predictions of several theoretical calculations, indicated by the different curves. The dotted curve represents a non-relativistic calculation by Blaazer [24]. The elementary production amplitude is calculated by evaluating the nuclear Born-term diagrams, the direct Δ term, and the ω-meson exchange diagram. The current operator used is the one by Dressler [25], which is similar to the one of Blomqvist and Laget [26]. No rescattering between the pion and the proton was included in this calculation.

The short-dashed curve is due to Lee [27], who uses the current operator of Nozawa, Blankleider and Lee [6]. The calculation contains basically the same ingredients as the one by Blaazer, but rescattering is included through Watson's theorem [5] by giving the calculated multipoles a phase, determined from the phase shifts extracted from pion-nucleon scattering.

The dash-dotted curve represents the calculation by Davidson [7, 28]. The main difference with the previous calculations is that the crossed Δ term is included, as well as the term for the exchange of a ρ meson, and that the calculation is relativistic. The influence of coupling to the $\pi^+ n$ channel, which is the dominant rescattering mechanism, was calculated by using a K-matrix approach, as described in Ref. [13]. It uses the scattering lengths for πN elastic and charge-exchange scattering. This approach, which is consistent with Watson's theorem, leads to a clear energy dependence of the E_{0+} multipole.

Finally, the ChPT results [29, 30] are indicated by the long-dashed curve. They result from a calculation in the framework of heavy-baryon chiral perturbation theory, in which all the tree diagrams and the diagrams with one pion loop were evaluated up to order q^4, plus one particular counter term at order q^5, and also the different π^0 and π^+ thresholds were taken into account. The recent photoproduction data and the present electroproduction data together with preliminary data from a similar experiment near threshold performed at Mainz [31] were used to fix two of the needed low-energy constants.

All calculations give a good description of the coefficient C, which implies that the value of the L_{0+} multipole is calculated more or less correctly. The effective-Lagrangian models give a fair to good description of A, but they understimate, some of them severely, the coefficient B, which means that the value of E_{0+} is underestimated. (Since the contribution of E_{0+} to A is relatively small, this does not prevent a fair description of the value of A.) ChPT gives a rather good description of the value of B, but here one should keep in mind that one of the low-energy constants, which determines the overall scale, was taken from the electroproduction data. The fact that ChPT overestimates the value of A at larger values of ΔW indicates that the value of the p-wave combination M_b is overestimated in the calculations.
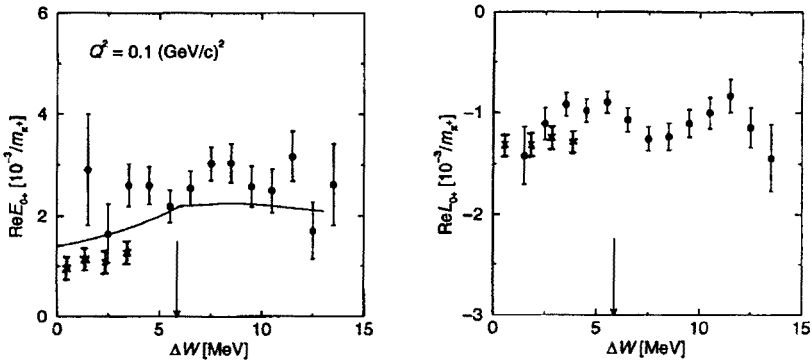
Fig. 4. Extracted values (black circles) of the real parts of the E_{0+} and L_{0+} multipoles at $Q^2 = 0.1$ (GeV/c)^2. The solid curve represents the value of the E_{0+} multipole at the photon point, shifted upwards by $2.7 \times 10^{-3}/m_{\pi^+}$. The arrows indicate the position of the $(\pi^+ n)$ threshold.

Finally it is worth observing that both theories that include explicitly the coupling to the π^+ channel (Davidson and ChPT) yield a good description of the value of B.

If a reliable estimate is available for the relevant combination of p-wave multipoles, the real parts of the s-wave multipoles E_{0+} and L_{0+} can be extracted from the values of the coefficients B and C (see Eq. 3 and note that the imaginary parts of the p-multipoles are very small near threshold). A recent LET calculation within ChPT for the p-wave multipoles by Bernard, Kaiser and Meißner [32, 29] was used to estimate the values of the E_{1+} multipole and the M_a combination. The values of M_a, as calculated by Blaazer, Davidson and Lee within their models, do not differ by more than 10% from this LET value.

The extracted E_{0+} and L_{0+} multipoles as a function of ΔW are shown in Fig. 4. As was mentioned before, values of E_{0+} at the photon point show a variation of about 0.8 units between the π^0 and π^+ thresholds. From Fig. 4 it is clear that within the error bars our data give no indication for such a variation, but they are not inconsistent with it either. In order to illustrate this variation, the value of the E_{0+} multipole at the photon point as a function of ΔW (taken from Ref. [16]) is drawn in Fig. 4. The curve has been shifted upwards by $2.7 \times 10^{-3}/m_{\pi^+}$ to globally account for the Q^2 dependence, calculated according to Ref. [3]. The value of the L_{0+} multipole shows a variation with W, especially just above the π^+ threshold, where L_{0+} becomes more negative.

Also indicated in Fig. 4 (crosses) are preliminary results from an experiment performed at Mainz [31]. Those values were determined from a longitudinal-transverse separation of cross sections measured very close to threshold at different beam energies. While the values for L_{0+} are in reasonably good agreement, those for E_{0+} show a discrepancy. Before drawing conclusions one has to await the final analysis and see the consistency between the values determined form the Rosenbluth separation and the pion angular distribution.
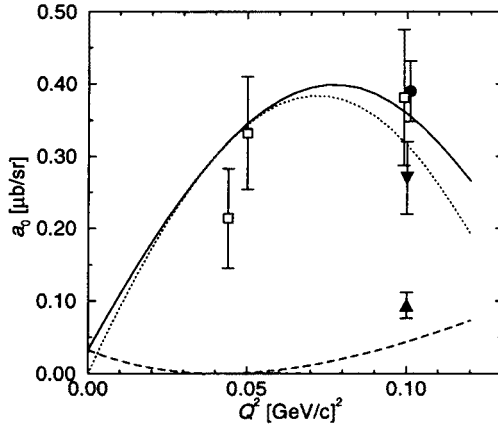

Fig. 5. Values of a_0 as a function of Q^2.

Our result for a_0 (black circle), as extracted from the value of A, together with the values of $|E_{0+}|^2$ (up-triangle) and $\epsilon_L |L_{0+}|^2$ (down-triangle) at threshold, are presented in Fig. 5. The values obtained by Welch *et al.* [17] (scaled for the different value of ϵ) are indicated by the open squares. The prediction for a_0 from ChPT [29, 30] is given by the solid curve. Also shown are the separate contributions of $|E_{0+}|^2$ (dashed) and $\epsilon_L |L_{0+}|^2$ (dotted), as calculated in ChPT. The value of E_{0+} is negative at $Q^2 = 0$, as determined in the photoproduction experiments, goes through zero near $Q^2 = 0.04$ (GeV/c)^2 and is positive at our value of Q^2. The value of L_{0+} is negative everywhere and goes from a value of -2.6 ± 0.5 (Ref. [17]) at $Q^2 = 0$ to -1.1 ± 0.1 at $Q^2 = 0.1$. It is interesting to note the decrease of $\epsilon_L |L_{0+}|^2$, which means an even larger one of $|L_{0+}|^2$, in the ChPT calculation. However, it has been remarked [1] that the one-loop corrections in ChPT become quite large at $Q^2 = 0.10$ (GeV/c)^2, and that therefore it is not clear if the one-loop expansion suffices.

Thus it seems that ChPT is able to give a good description of the presently available photo-and electro-production data. Since some low-

energy constants needed in the calculations were taken form those data, the calculations should further be checked by having additional electro-production data, notably in the range $Q^2 = 0.04 - 0.06$ (GeV/c)^2. Such experiments are being performed at Mainz.

3. Coherent π^0 production on ^{4}He

As already mentioned in the introduction, pion production on a nucleus contains the following ingredients: the elementary production amplitude, the nuclear structure and the propagation and decay of the Δ in a nuclear medium. The interest is especially in the latter, since it contains the ΔN and πN interaction in a nuclear medium. In the Δ-hole model [33] pion production is described by the formation of a Δ-hole state and a delta propagator including Pauli blocking, an operator describing intermediate π^0 propagation and a spreading potential for the coupling to more complicated nuclear states. Another approach is the Distorted Wave Impulse Approximation [34], in which the interaction of the outgoing pion with the nucleus is described by a (phenomenological) optical potential, thus implicitly accounting for the Δ degrees of freedom.

These processes will be studied at NIKHEF with the ^{4}He(e,e'π^0)^{4}He reaction [35]. The choice of coherent π^0 production on ^{4}He was motivated by the following reasons. Since the initial and final nuclear state are the same, there are effectively no nuclear structure uncertainties. This can be seen from the PWIA formula for the cross section, which reads:

$$\sigma^{PW} \sim \sigma_{\pi N} A^2 F^2(-t), \tag{5}$$

where $F(-t)$ is the matter form factor, which depends on the momentum transfer t to the nucleus. Assuming the proton and neutron densities in ^{4}He to be the same, this matter form factor is well known from the measurements of the charge distribution of ^{4}He with elastic electron scattering.

Furthermore π^0 production has the property that in the Δ region it is for more than 90% due to resonance production, in contrast to charged pion production, where the Born terms are responsible for about 50%, even at the top of the Δ resonance.

Finally, since the nucleus ^{4}He has $J^\pi = 0^+$, only magnetic multipoles (and then only the non spin-flip parts) contribute, notably M_{1+} and M_{1-}. The cross section reads:

$$\frac{d\sigma}{d\Omega_\pi^*} = \frac{p_\pi^*}{q_L}\frac{W}{m_p}|M_b|^2 \sin^2\theta_\pi^* \left[\, 1 - \epsilon\cos(2\phi_\pi^*)\,\right] \tag{6}$$

with $M_b = 2M_{1+} + M_{1-}$ (NB. M_b 'contains' F!). Thus even without a longitudinal/transverse separation one can sensitively test calculations, *e.g.*by

comparing the M_b multipole combination to the corresponding one for free nucleons.

The data situation is very marginal. There are some results from photoproduction, but none at all from electroproduction. This is largely due to the difficulty in detecting the π^0 and in separating coherent production from processes in which the final nucleus ^{4}He gets excited. The best data sets are from experiments at Orsay [36] and Bates [37], as shown in Fig. 6. The curves are the results of Δ-hole [33] (dash-dotted) and DWIA calculations [38].
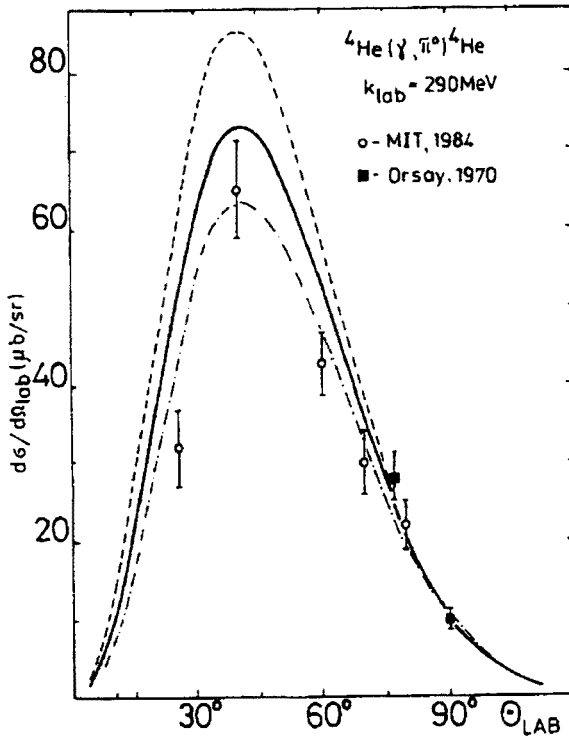

Fig. 6. Data for π^0 (photo)production on ^{4}He.

Like in the ^{1}H(e,e'π^0)p case, the best way to measure the ^{4}He(e,e'π^0)^{4}He reaction is to detect the recoiling ^{4}He nucleus. However, the recoil energy can be rather small and spans a large range, see Fig. 7. Hence very thin targets (less than 1 mg/cm^2) and a detector that can detect and identify a few MeV alpha particles are needed. Realistically such experiments can only be performed by using the large current of the circulating beam in a

storage ring together with a gas jet or gas 'dwell cell' target. This method
is used in the NIKHEF experiment by using the internal target set-up in
the AmPS ring [21]. With an (average) electron current of 50-80 mA and
an open gas cell (diameter 15 mm, length 40 cm, T = 20 K), which yields a
target density of up to 2×10^{15} at/cm^2 (at a flow of 2×10^{16} at/s), luminosities
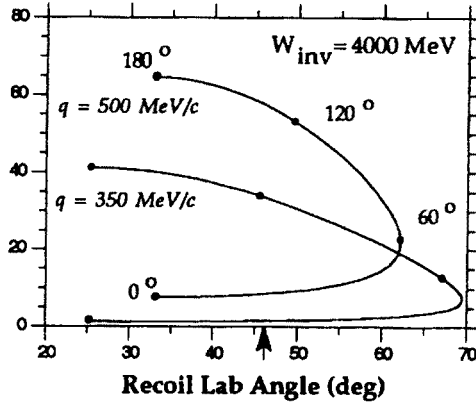of about 10^{33} at/cm^{2}s seem feasible.

Fig. 7. Kinematics for the ^{4}He(e,e'π^0)^{4}He reaction.

In order to detect and identify the alpha particles a special detector, see
Fig. 8, has been developed. It consists of a low-pressure MWPC followed
by two layers of Si strip detectors and a plastic scintillator. For particles
of short range the MWPC and first Si layer act as a ΔE or time of flight
- E system. For more penetrating particles that do not give enough pulse
height in the MWPC, the two Si layers provide particle identification and
energy determination via the $\Delta E - E$ method. The scintillator is used as
an E counter for higher energy particles. Position information is provided
by the MWPC (y), the first Si layer (x) and the second Si layer (y again).
The energy resolution is about 200 keV and the position resolution is 3 mm.
The detector will also be used for other experiments, like studies of quasi-
free pion production (^{4}He(e,e'π^0p)^{3}H) and of correlations (^{4}He(e,e'pn)^{2}H).

The scattered electron will be detected in a large solid-angle, large mo-
mentum bite magnetic spectrometer ('Bigbite'). The experiment will cover
an energy range of about 150 MeV in the Δ region, and the full θ_π^* angular
distribution will be measured with one setting of the recoil detector.

Estimated count rates for $E_e = 675$ MeV, $\theta_{e'} = 30°$, which yields a value
of the linear momentum transfer q in the Δ region of about 400 MeV/c
($Q^2 \approx 0.065$ (GeV/c)^2), are about 50 per hour at a luminosity of 10^{33}
at/cm^{2}s.

MWPC (5 x 15 cm²)

Si-x Si-y Plastic scintillator

5 torr
isobutane

Si-strip detectors,
5 x 5 cm² each with
16 x 3 mm strips

3 horizontal detectors,
100 μm depletion depth

3 vertical detectors,
300 μm depletion depth

1 μm mylar

pre-cathode (-)
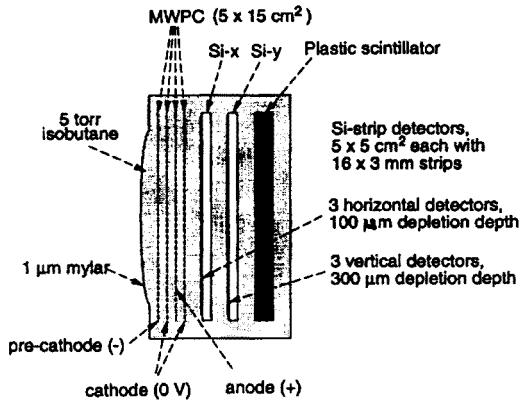
cathode (0 V)   anode (+)

Fig. 8. Lay-out of the recoil detector.

The data at large values of θ_π^* which is equivalent to large values of $-t$, will be interesting for an additional reason. In the ^{3}He$(\gamma, \pi^+)^3$H reaction it has been observed that the cross section at values of $-t$ of 8 - 13 fm^{-2} are two orders of magnitude larger than the ones calculated in DWIA, even if charge-exchange in the final state is included [39]. A two-body mechanism, where the photon is absorbed on one nucleon and the pion is emitted from another nucleon, reduces the discrepancy between data and theory considerably. It will be very interesting to study this in more detail in the ^{4}He$(e,e'\pi^0)^4$He reaction, in which the same phenomenon is expected to be present.

4. Summary and outlook

Data on photo- and electroproduction of neutral pions on nucleons near threshold are of great interest for Chiral Perturbation Theory and for Hamiltonian models of pion production and πN scattering at very low pion energies. The existing data on the proton at $Q^2 = 0$ and 0.10 (GeV/c)^2 are fairly well described. More experiments are needed to establish the consistency between the photo- and electroproduction results and to study the Q^2 dependence in the intermediate region. The latter is especially important as a further check on the ChPT calculations, since they have used the existing data to fix some of the needed low-energy constants. Since the outgoing proton energy will be reduced when going to lower values of Q^2, a liquid H$_2$ target can not be used anymore, because the energy loss and angle straggling become too large. A target as used in the NIKHEF experiment allows for a flexible adjustment of the density.

The challenge for the Hamiltonian models will be to incorporate consistently gauge invariance and the full low-energy πN dynamics, including *e.g.*charge exchange.

Obviously data on π^0 production on the neutron are of the highest importance. Realistically these can only be obtained from coherent π^0 production on the deuteron. There are proposals for such studies at SAL (with real photons) and NIKHEF (electroproduction).

The technique of recoil detection near the internal beam of a storage ring will allow one to study π^0 production also in heavier systems. Thus *e.g.*Δ propagation and decay in the helium isotopes can be investigated both with coherent and with quasi-free pion production.

Finally the inclusion of the polarization degree of freedom (linearly polarized photons and polarized electrons and targets, *e.g.*$^3\vec{He}$) will allow even more detailed comparisons with theoretical models.

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