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Mainz Microtron MAMI

Collaboration A1: "Virtual Photons"

Spokesperson: R. Neuhausen

Proposal for an Experiment

Threshold Measurement of the Coherent $d(e, e'd)\pi^o$ Reaction

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Abstract

We request **250 hours** of beam time to perform a first measurement of the near threshold, coherent $d(e,e'd)\pi^o$ reaction around $q^2 = -0.075 GeV^2/c^2$. The experiment would detect recoil deuterons emerging from the target. A Rosenbluth separation will be performed to determine the longitudinal and transverse contributions. The ϕ dependence of the cross section will be used to obtain the interference structure response. This is the same technique as has been used for the successful study of the $p(e,e'p)\pi^o$ reaction. The main ingredients of the cross section are the isovector even s wave pion production amplitudes and multiple scattering (including pion-nucleon charge exchange) in the intermediate states. The experiment will be instrumental in stimulating and checking ChPT and model calculations of this fundamental process.

1 Introduction

The study of photo and electroproduction of pions from the nucleon is fundamental because of the special properties of Goldstone Bosons in QCD. In particular the fact that in the limit in which the up and down quark masses approach zero, the pion mass and its interactions with hadrons in the low momentum limit would also approach zero [Do92]. In the real world in which the up and down quark masses are small but non-zero the pion mass and its low energy interactions are small. The calculation of these effects is handled by a QCD related approximation scheme known as chiral dynamics or chiral perturbation theory (ChPT) [We79, Do92, Be95]. Testing this (or any other) QCD approximation scheme is of fundamental importance. In particular any experiment which measures the production and interaction of Goldstone Bosons with other hadrons is part of a general program of confinement scale QCD physics and will become one of the tests for any theoretical prediction.

In principle calculations in the NN and $NN-\pi$ sectors can be performed with ChPT. In practice ChPT is easiest to handle in the purely Goldstone Boson sector where calculations up to two loops have been performed (see e.g. the contribution of Gasser in [Be95]). In the $\pi - N$ sector calculations up to one loop have only recently been performed [Ber95]. Despite technical difficulties progress in the NN sector has been made by Weinberg and collaborators [We90, vK92]. One loop ChPT calculations to $O(q^3)$ have been performed on the threshold coherent $d(\gamma,\pi^o)d$ reaction [Ber95]. Most recently these calculations have been improved to $O(q^4)$ and the results should be available soon [Bea96].

The main ingredients of the $\gamma^* + N \to \pi^0 + N$ reaction in ChPT [Ber92] are the direct (Born plus counter-term) and the pion rescattering (loop) terms. For the coherent $\gamma^* + d \to \pi^0 + d$ reaction the relative weight of the pion rescattering terms are enhanced relative to the direct terms because the pion can now interact with two nucleons. There is in addition a meson exchange current term in which the photon interacts with the charged pion being exchanged by the two nucleons. Therefore the coherent $\gamma^* + d \to \pi^0 + d$ reaction brings in several new ingredients:

1. the coherent sum of $\gamma^* + n \to \pi^0 + n$ and $\gamma^* + p \to \pi^0 + p$ amplitudes;
2. enhanced pion-nucleon rescattering effects;
3. meson current contribution; and
4. deuteron structure effects.

These are all fundamental effects in confinement scale QCD/nuclear physics studies which we would like to study. We anticipate that this experiment will stimulate new calculations of this fundamental process which this data can be used to test.

In recent years there has been a great deal of progress in the study of pion photo and electroproduction from the proton. Here we shall present only a very brief summary. Recent experiments at Saskatoon [Berg96] and at Mainz with the TAPS detector [Fu96] have clearly shown that the old low energy theorems are incorrect which was previously predicted by one loop ChPT to $O(q^4)$ [Ber92]. In addition the predicted unitary cusp [Fa80, Ber92, Be96, Berg96] has been observed for the s wave production multipole E_{0+} and is presented in Fig. 1. This is caused by the two step $\gamma + p \to n + \pi^+ \to p + \pi^o$ reaction. It causes a rapid variation in the real part of the E_{0+} multipole below the $n\pi^+$ threshold and in the imaginary part above the charged pion threshold. The results to date are consistent with the predictions of ChPT [Ber92]. In addition to the data shown last year this reaction has been measured at Mainz with linearly polarized photons [Bec95]. This data will further test the ChPT calculations.

Starting with calculations based on current algebra and PCAC low energy theorems (LET) for the s wave multipole E_{0+} in pion photoproduction were derived [deB70]. More recent calculations based on ChPT have shown that the original derivations were incomplete [Ec95]. From Fig. 1 it can be seen that the threshold value of $E_{0+} = -1.3 \pm 0.2$ (in the usual units of $10^{-3}/m_{\pi^+}$) are in disagreement with the old LET predictions [deB70] of -2.3 but are in agreement with the new ChPT fits (there are two low energy constants which must be fit to this multipole) [Ber92]. It should be pointed out that there is a ChPT prediction for $E_{0+}(\gamma + n \rightarrow \pi^o + n)$ which has no additional free parameters. In addition we note that there are new LET derived for the p wave multipoles in photoproduction [Ber92, Ec95] and electroproduction [Ber95, Ber95]. These are consistent with experiment for photoproduction [Berg96, Fu96]. They will be tested in a more precise way in photoproduction by the new Mainz data with polarized photons [Bec95] and will be tested in electroproduction for the first time by the new Mainz data [A1/95].

For electroproduction there have been completed measurements at NIKHEF [vanB95] and at Mainz [Di96] at $q^2 = -0.1 GeV^2/c^2$. These measurements indicate that $E_{0+}(q^2)$ has changed sign somewhere between the photon point and $q^2 = -0.1 GeV^2/c^2$. The ChPT calculations indicate that this should occur around $q^2 = -0.04 GeV^2/c^2$ [Ber95]. In a more recent experiment at Mainz [A1/95] we have taken more data at smaller magnitudes of q^2 in order to determine more precisely where $E_{0+}(q^2)$ changes sign. This data is still under analysis.

The ChPT calculations of threshold electroproduction have been carried out to one loop and $O(q^4)$ with the exception of the s wave multipoles which have been

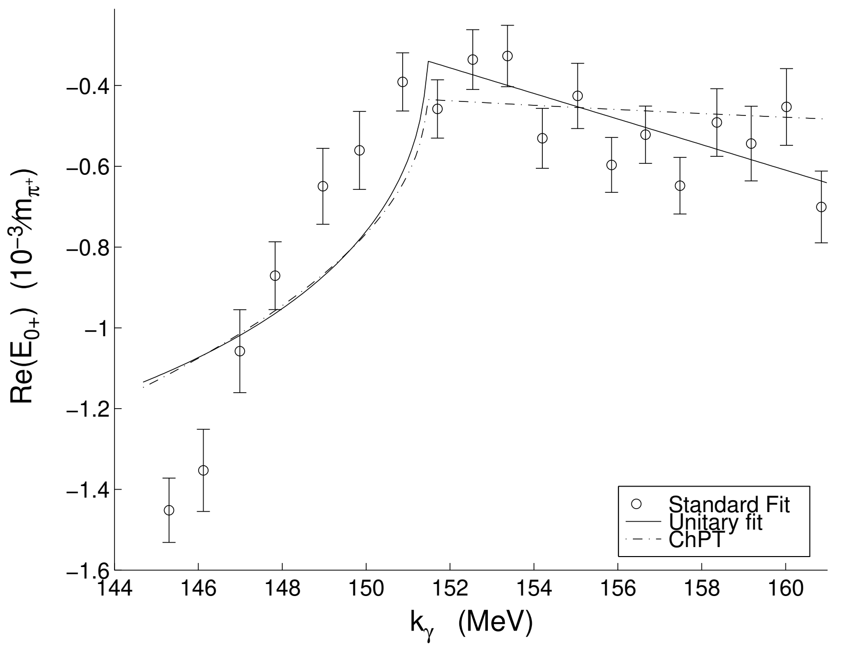

Figure 1: The cusp in the E_{0+} amplitude as observed in [Fu96].

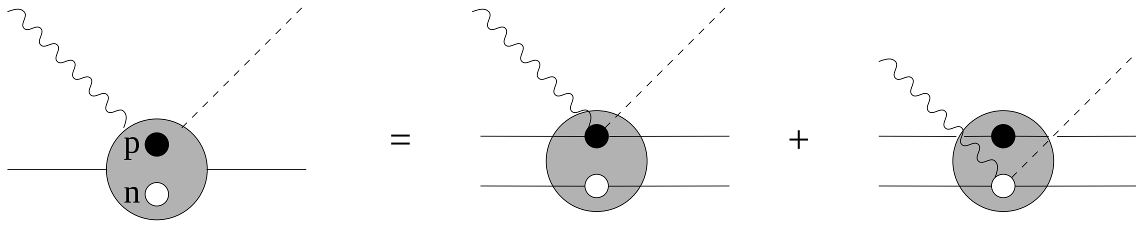

Figure 2: Impulse approximation: The coherent amplitude on the deuteron is given by the sum of the neutron and proton amplitudes.

carried out to $O(q^5)$ [Ber95]. In this calculation there are five low energy parameters which must be fit to the data. Three of them are fit to the photoproduction data, one to the nucleon form factor RMS radius, and one has been fit to the existing data at $q^2 = -0.1 GeV^2/c^2$. This means that any additional data for the $ep \rightarrow e'p\pi^o$ and $en \rightarrow e'n\pi^o$ reactions can be compared to the calculations without any additional parameters!

It is of great interest to extend these measurements to the $\gamma^* + n \rightarrow n + \pi^o$ reaction (where γ^* is real or virtual). There are several reasons for this. First of all there are significant violations of isospin predicted for the threshold $\gamma^* + N \rightarrow \pi + N$ reaction [Ber92, Ber95, Be96]. The largest of these is due to the threshold difference between the four exit channels which would not exist if isospin were strictly conserved. In addition to this there is a dynamics isospin violation [Be96] which is related to a predicted isospin breaking in low energy πN scattering [We79] caused by the mass difference between the up and down quarks [We79, Ga82]. Since there are three independent isospin amplitudes in the $\gamma^* + N \rightarrow \pi + N$ reaction one must measure all four final reaction products to test for a possible isospin violation.

An additional reason to make the $\gamma + n \rightarrow \pi^o + n$ measurement is to check the predictions of ChPT [Ber92]. As is well known ChPT calculations incur low energy constants which must be determined empirically. For the one loop calculations of $O(q^4)$ for the $\gamma + p \rightarrow \pi^o + p$ reaction there are 3 low energy parameters. However for the neutron there are no additional parameters so that for this case we have a prediction. As is often the case this good theoretical reason is complemented by an additional difficulty, in this case the absence of neutron targets. The simplest nuclear system is the deuteron. However there are additional complications due to the two nucleon character of the system.

As was suggested above the initial motivation to study the $\gamma^* + d \rightarrow \pi^0 + d$ reaction is to try to measure the $\gamma^* + n \rightarrow \pi^o + n$ amplitude. Many years ago at Saclay and Bates an attempt was made to do just this for real photons [Ar78]. In the impulse approximation (Fig. 2) one encounters the isovector even $\gamma^* + N^{(+)} \rightarrow \pi^o + N^{(+)}$ amplitude where $N^{(+)}$ is the $n + p$ amplitude. However as has been known for a long time there are very large multiple scattering corrections to the impulse approximation [Ko77], and the simple attempt to measure the neutron amplitude failed. The multiple scattering diagrams that were used for the ChPT calculation [Bea95] are presented in Fig. 3. Exactly at threshold in the Coulomb gauge only diagrams (a) and (b) contribute [Bea95]. With these corrections one can write the electric dipole amplitude for the deuteron E^d_{0+} as [Bea95]:

$$E^d_{0+} = E^{ss}_{0+} + E^{(a)}_{0+} + E^{(b)}_{0+}$$

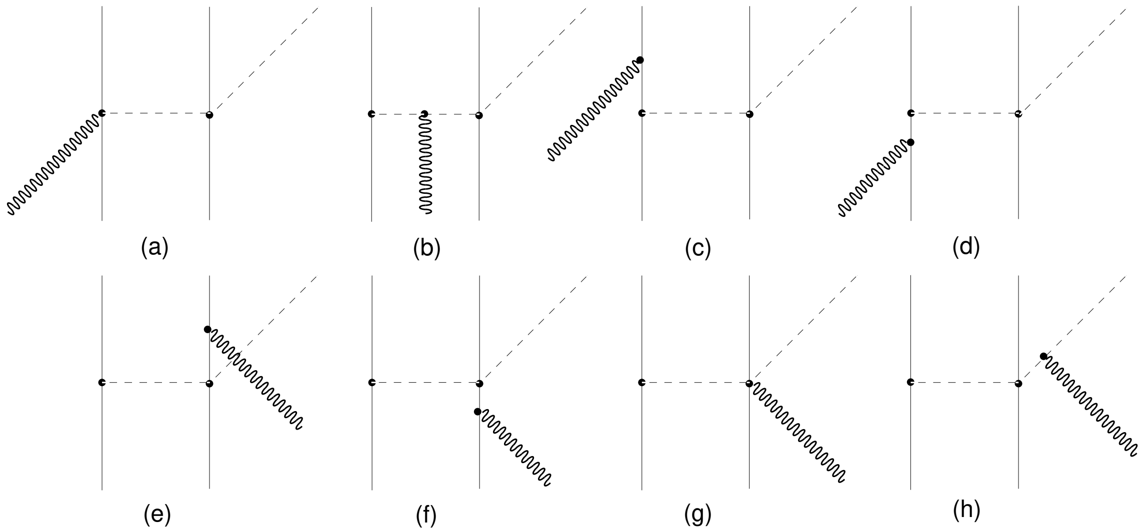

Figure 3: The multiple scattering diagrams as used in [Bea95]. In the Coulomb gauge only graphs (a) and (b) contribute.

where

$$\begin{aligned} E_{0+}^{ss} &= \text{single scattering value} = f \cdot S(k/2) \cdot (E_{0+}^{p\pi^o} + E_{0+}^{n\pi^o}) \\ f &= (1+\mu)/(1+\mu/2) \\ \mu &= m_\pi/M \\ k & \quad \text{is the photon energy} \\ S(k/2) & \quad \text{is the deuteron form factor} \end{aligned}$$

The calculated values in ChPT for the multiple scattering terms [Bea96] are presented in Table 1. It can be seen that the multiple scattering terms $E_{0+}^{(a)} + E_{0+}^{(b)}$ are larger then the single scattering term $E_{0+}^{(ss)}$ which confirms the original multiple scattering calculations [Ko77]. The value for $f \cdot S(k/2) = 0.84$ [Bea96] shows that there is a large sensitivity to $E_{0+}^{\pi^0 n}$. This can also be seen in Table 1 because we have shown the values for the threshold neutron and proton with the ChPT [Ber92] and low energy theorem [deB70] predictions. These give a significant for E_{0+}^{d} which should be easy to distinguish. Because of the large two nucleon contributions to E_{0+}^{d} it is clear that one will need to be very confident about the theory to extract an accurate value for $E_{0+}^{\pi^0 n}$. It should be noted that this is precisely what is being claimed for the ChPT calculations [Bea96]. This is based in part on the fact that it has been shown that there is very little dependence on the NN potential [Bea96].

From this table it is clear that there is a large sensitivity to $E_{0+}^{\pi^o n}$. On the other hand it has also been confirmed again that the multiple scattering corrections [Ko77] are very large. It will therefore not be very easy to extract a precision value of $E_{0+}^{\pi^o n}$ from the coherent $\gamma + d \to \pi^o + d$ reaction unless we are confident that the calculation of the multiple scattering terms have been performed with a small error.

The ChPT calculations are very interesting because of their connection to QCD. However they are just beginning. They need to be extended to energies above threshold, to include the p wave contributions, and to be extended to electroproduction. We have been informed that these developments are in progress [Bea96]. Of course

	ChPT	PCAC
$E_{0+}^{\pi^o p}$	-1.16	-2.28
$E_{0+}^{\pi^o n}$	2.13	0.50
$E_{0+}(p+n)$	0.97	-1.78
E_{0+}^{ss}	0.81	-1.50
$E_{0+}^{(a)} + E_{0+}^{(b)}$	-2.15	-2.15
E_{0+}^{d}	-1.34	-3.65

Table 1: Values for E_{0+} for the $\gamma + d \rightarrow \pi + d$ Reaction in units of $10^{-3}/m_{\pi^+}$.

they need to be tested against experimental data.

By contrast there are several model calculations for the coherent $d(\gamma^*, \pi^o)$ process [Bl94, Ga95, Ka96, Wi95]. These have the advantage of using more tested ingredients such as empirical NN potentials and modern deuteron wave functions so that the deuteron structure aspects should be accurately represented. Furthermore since there are a number of NN potentials to compare to the sensitivity to this can be readily quantified. Model calculations also have a larger energy region of validity which includes the $\Delta(1232)$ and possibly higher resonances, and have been much more tested by comparison with data.

In this proposal we shall only briefly make a few remarks about the model calculations since they are more familiar. Blaazer, Bakker, and Boersma [Bl94] use a Faddeev approach to calculate the final state $\pi - \pi - N$ system. Garcilazo and deGuerra use a relativistic Feynman diagram approach [Ga95]. Kamalov, Tiator, and Bennhold use a coupled channels approach with the KMT multiple scattering formalism to describe the final state interactions [Ka96]. They describe both elastic pion-deuteron scattering as well as the coherent π^o photoproduction. Wilhelm and Arenhövel use a $NN - N\Delta$ coupled channel approach to describe deuteron photo disintegration and coherent π^o photoproduction [Wi95]. Only one of these model calculations has been performed for electroproduction [Bl94] but we believe that data will motivate the extension of the other model calculations.

All of the model calculations stress polarization observables. In particular an interesting tensor polarization observable has been pointed out which is uniquely sensitive to either exchange or d state effects [Wi95]. In a manner which is analogous to study the d state admixtures in the N to Δ transition we expect that the study of longitudinal-transverse interference terms in electroproduction will show this kind of sensitivity even more then photoproduction. In addition coherent electroproduction is easier to observe since at the higher q^2 magnitudes allows the deuteron to escape from the target.

We believe that this is an interesting physical situation. There are many different theoretical methods to calculate the coherent photo and electro production of π^o mesons from the deuteron. All of them have some advantages and disadvantages. The main point is that this is a fundamental reaction in the very special and important two nucleon system and that it should be studied in its own right. We take the point of view that it is up to the theory to demonstrate that it is up to the task of accurately calculating the entire process. The main ingredients are the sum of the neutron and proton π^o electric dipole production amplitudes, the multipole scattering terms, and the deuteron structure. The latter has been well tested in this kinematic regime in electron scattering and in the $d(\gamma, p)$ and $d(e, e'p)$ reactions. The $\gamma^* + p \rightarrow \pi^o + p$ reaction is also been well studied. This means that the main uncertainties are the neutron-π^o amplitude and the multiple scattering terms. These are both of fundamental interest and it is a challenge to theory to accurately calculate them. This proposed experiment should provide a testing ground of all of these calculations.

From an experimental point of view the proposed study is similar to the experiments which are being accurately studied at MAMI such as the $ep \rightarrow e'p\pi^o$ and $e'p\gamma$ reactions in which the recoil proton is detected. In this case the recoil deuteron will be detected. As will be discussed below it can be shown that the only (minor) difficulty is that since dE/dx for the deuteron is larger then for the proton one will be restricted to somewhat larger magnitudes of q^2 for the deuteron case. This will be addressed in the experimental section. We also note that the magnitude of the cross section is sufficient to obtain the desired statistical accuracy. The questions of the systematic error have been solved in the proton experiments.

2 Experiment

As mentioned before, the feasibility of this experiment and the more than sufficient resolution of the A1 three spectrometer setup have been proven in a previous experiment (A1-1/94, Threshold pion electroproduction).

Similar to the electroproduction off the proton, the cross section for pion production on unpolarized deuteron, both in initial and final state, is given by five structure functions $f(\theta)$ [Ar88]:

$$\begin{aligned}\frac{d\sigma}{dE'd\Omega'd\Omega^*} &= \Gamma_t(f_T(\theta) + \epsilon f_L(\theta) + \epsilon f_{TT}(\theta)\cos 2\phi \\ &\quad + \sqrt{\epsilon(1+\epsilon)} f_{TL}(\theta)\cos\phi + h\sqrt{\epsilon(1-\epsilon)} f_{TL'}(\theta)\sin\phi)\end{aligned}$$

with

$$\begin{aligned} \epsilon &= \left(1 - \tfrac{2(\omega^2-q^2)}{q^2} tan^2 \tfrac{\theta_e}{2}\right)^{-1} & \Gamma_t &= \tfrac{\alpha}{2\pi^2}\tfrac{E'}{E}\tfrac{k_\gamma}{(-q^2)}\tfrac{1}{1-\epsilon} \\ k_\gamma &= \tfrac{W^2-M^2}{2M} & k^*_\gamma &= \tfrac{M}{W}k_\gamma = \tfrac{W^2-M^2}{2W} \end{aligned}$$

where W: CMS energy, M: deuteron mass, θ_e: electron scattering angle, h: beam helicity.

The test of ChPT will be concentrated on determining E^d_{0+}, which is related to the transverse structure function f_T close to threshold by (notice, that in the literature different normalisations are in use):

$$f_T = \frac{p^*_\pi}{|\vec{k}|}\frac{8}{3}|E^d_{0+}|^2$$

To separate f_T and f_L we need to perform a Rosenbluth separation by varying ϵ. By the complete out of plane coverage (ϕ) at threshold we will be able to separate the transverse-transverse interference f_{TT} and the transverse-longitudinal interference f_{TL}. With polarized electron beam we would be able to access $f_{TL'}$ in addition, but at the moment it is not clear that the Møller polarimeter will be installed for this measurement. With these structure functions we will be able to determine at least three independent p wave combinations to extrapolate s and p waves down to the threshold.

Fig. 4 shows the deuteron laboratory angle and laboratory momentum for $q^2 = -0.075 GeV^2/c^2$. The rectangle shows the spectrometer acceptance of spectrometer A, which will be used to detect the deuteron. We will be able to cover the complete CMS solid angle from threshold region up to $\approx 3 MeV$ above threshold.

Our $p(e,e'p)\pi^o$ measurement covered a laboratory momentum for the proton down to $150 MeV/c$. This can't be reached for the deuteron, since the energy loss dE/dx for deuterons in a deuteron target is considerable higher. We will restrict ourself to a minimum deuteron laboratory momentum of $\approx 250 MeV/c$. With this restriction we can still measure in the threshold region for a four-momentum transfer of $q^2 = -0.06 GeV^2/c^2$. For this q^2 value the deuteron laboratory momentum at threshold is $270 MeV/c$. In addition we choose a measurement at $q^2 = -0.1 GeV^2/c$ to complement our extended measurements for p(e,e p) pi0 [Di96] at this point.

Table 2 shows the proposed settings. For all three q^2 settings we intend to perform a three ϵ Rosenbluth separation. The ϵ range is given by the maximum

MAMI beam energy of 855MeV and the minimum angle of spectrometer A of 21°. The high ϵ point will be measured with spectrometer B ($\Omega = 5.6msr$, $8° < \theta_e < 60°$), the low ϵ point with spectrometer C ($\Omega = 21msr$, $\theta_e > 50°$). A third ϵ point in the middle between the maximum and the minimum can be reached for all three q^2 values with both electron spectrometers, so we can match the spectrometers with these settings.

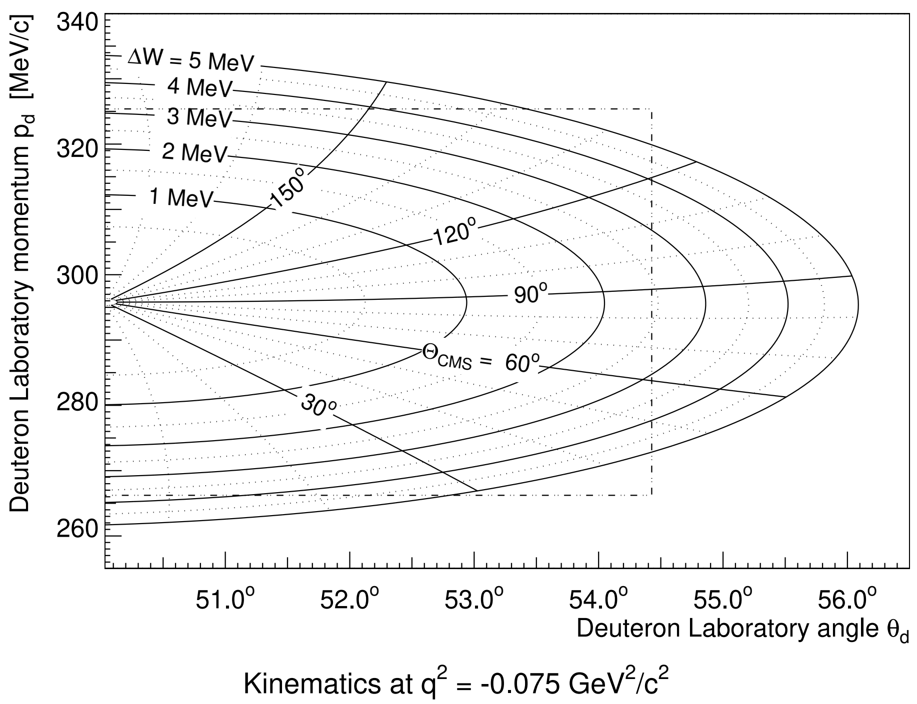

Figure 4: Deuteron laboratory momentum and laboratory angle at $q^2 = -0.075GeV^2/c^2$ as function of the CMS energy ΔW and of the pion CMS angle θ^*_π.

3 Count Rate Estimate

We can estimate the cross section for $d(e, e'd)\pi^o$ by comparing the photoproduction cross sections of $d(\gamma, \pi^o)d$ and $p(\gamma, \pi^o)p$. This ratio is determined experimentally at threshold by [Fu96, Ar78]:

$$\frac{\sigma(\gamma d \to d\pi^o)}{\sigma(\gamma p \to p\pi^o)} = \frac{p_\pi/|k| \cdot 8/3 \cdot |E_{0+}^{\gamma *}|^2}{p_\pi/|k||E_{0+}^{\gamma}|^2} = \frac{|-3.7|^2}{|-1.3|^2} = 8.1$$

This value might be for count rate estimates to high, since even close to threshold the p wave contributions dominate. Fig. 5 shows the cross section as measured by [Ar78]. From this a ratio of ≈ 4 at 5 MeV above threshold seems to be more realistic and was used in our count rate estimates.

About the longitudinal cross section we have no information at the moment, so we assume that it might be in the same order of magnitude as for $p(e, e'p)\pi^o$.

We estimated the count rates by Monte Carlo simulation, assuming a very conservative Luminosity of

$$L = 5\frac{MHz}{\mu barn}.$$

Our target system ("Basel Loop" cryo target) is able to stand luminosities 10 times as high as this, but we will be restricted by the polarized electron source if we intend to measure the fifth structure function and by current in the wire chambers of the proton spectrometer.

The result of the estimates are given in the last column of table 2. We consider these count rates to be very conservative. Table 3 summerises the additional time we will need for calibrations and setup changes. The settings x-2b are assumed with the same time as the settings x-2 since we can compensate for the smaller cross section by higher beam current. For this matching of the spectrometers B and C there is no polarized beam necessary.

	ϵ	q^2 $[GeV^2/c^2]$	E_0 $[MeV]$	E' $[MeV/c]$	p_p $[MeV/c]$	θ_e	θ_p	Counts $\times 10^3$
1-1	0.920	-0.075	855	695	296	20.5°	50.0°	80 in 10h
1-2	0.586	-0.075	390	230	296	54.4°	36.2°	36 in 15h
1-3	0.252	-0.075	285	125	296	92.9°	23.2°	32 in 20h
2-1	0.898	-0.10	855	688	333	23.8°	51.0°	78 in 10h
2-2	0.561	-0.10	420	253	333	58.0°	37.0°	36 in 15h
2-3	0.191	-0.10	300	133	333	104.4°	21.2°	36 in 30h
3-1	0.933	-0.06	855	699	270	18.2°	48.9°	99 in 10h
3-2	0.615	-0.06	375	219	270	50.6°	35.7°	36 in 14h
3-3	0.273	-0.06	270	114	270	88.5°	23.2°	32 in 20h
Σ								144h

Table 2: Settings for the experiment.

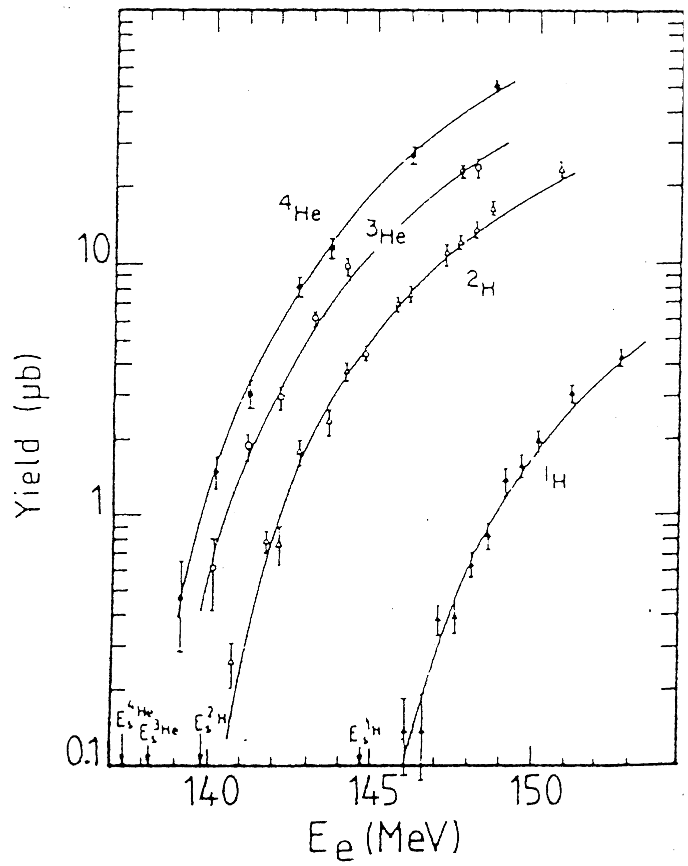

Figure 5: The measured π^o yields of [Ar78] as function of the Bremsstrahlung endpoint energy. The yield is related to the cross section by integrating over the Bremsstrahlung spectrum and the accepted solid angle. The curves are the theoretical yields calculated with DWIA cross sections, adjusted to the data.

4× Energy change	16 h
4× Setup change	4h
Matching of spectrometer B and C:	
1-2b	15h
2-2b	15h
3-2b	14h
Calibration Electron Arm ($^{12}C(e,e'p)$):	
C at 130 MeV	10h
B at 690 MeV	10h
B at 230 MeV	10h
C at 230 MeV	10h
Σ	104h

Table 3: Calibration and setup change overhead. Settings x-2b are repeated with spectrometer B, but with higher luminosity to compensate for the smaller solid angle (with unpolarized beam!).

4 Conclusion

We consider the $d(e,e'd)\pi^o$ experiment as an important extension of our pion threshold program we started with $p(e,e'p)\pi^o$. This will be a first measurement of this process and we expect it to stimulate further ChPT and model calculations. The proposed experiments will provide a check of these calculations. This is an important arena since the physics includes both the coherent sum of the s wave nucleon amplitudes $E_0^{\pi^0 p} + E_{0+}^{\pi^0 n}$ and multiple scattering terms which are larger then in free nucleon case since they include two nucleon terms. This is timely since there are now ChPT and model calculations of the real photon induced process. The experiment is feasible since it will utilise the same experimental technique as we have employed in the successful $p(e,e'p)\pi^0$ experiments. It also has higher count rates since we anticipate that the cross sections are larger.

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