

Opening Remarks: Experimental Tests of Chiral Symmetry Breaking

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A physical introduction to the basics of chiral dynamics is presented. Emphasis is placed on experimental tests which have generally demonstrated a strong confirmation of the predictions of chiral perturbation theory, a low energy effective field theory of QCD. Special attention is paid to a few cases where discrepancies exist, requiring further work. Some desirable future tests are also recommended.

Keywords: Chiral Physics, QCD

1. Introduction: Brief History of this Workshop Series and an Introduction to Chiral Dynamics

This workshop is the fifth of a series dedicated to Chiral Dynamics: Theory and Experiment that Barry Holstein and I started at MIT in 1994.¹ At that time, the theory was generally far ahead of experiments, and we decided that it was important to start serious discussions in which the experimental aspects of the field would be treated on an equal footing with the theory. We also decided that it should be a workshop (not a conference) allowing plenty of time for active discussion. The format of having plenary talks in the mornings and working groups in the afternoons was established. Our goal was to evaluate what had happened in the field in the last few years and to discuss where we should go in the near future. In the early period of the workshops we decided to have them every three years and to alternate between Europe and the U.S. We have now had workshops in Mainz (1997²), Jefferson Lab (2000³), Bonn (2003⁴), and now at Duke. I am very proud that this series has become an important measure of the progress of this field.

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As the first speaker of this workshop I thought that it was important to introduce some of the terminology and concepts of chiral dynamics and the experiments that test its theoretical predictions. As is well known the coupling between quarks in QCD increases at low energies (for an introduction to QCD and chiral dynamics see e.g.⁵) which leads to confinement. This has the consequence that normal perturbation theory does not work at low energies. However there is a low energy effective theory known as chiral perturbation theory(ChPT).⁵⁻⁷ The QCD Lagrangian can be written as a sum of two terms, L_0 which is independent of the light quark masses (up, down, strange) and L_m which contains the masses of the three light quarks. Consider the chiral limit in which the three light quark masses $m_q \rightarrow 0$. The solutions to the Dirac equation for massless quarks have a definite chirality or equivalently helicity $= \hat{\sigma} \cdot \hat{p} = \pm 1$. The terminology is that when the quark spin $\hat{\sigma}$ is parallel (anti-parallel) to the momentum vector \hat{p} , the quark is labeled as right(left) handed. For massless quarks, the left and right handed solutions are independent and this is known as chiral symmetry. Another language to express this is that there are separate conservation laws for vector (left +right) currents and axial vector(left- right) currents.⁵ As is well known, the vector current is conserved while the axial vector current is conserved only in the chiral limit (i.e. $m_q \rightarrow 0$) and slightly non-conserved in the real world. This is one of the approximate symmetries of QCD which was earlier known as current algebra/PCAC(partially conserved axial currents).⁵

Despite the fact that the light quark mass independent part of the QCD Lagrangian L_0 , has chiral symmetry, matter does not seem to obey the rules. The chiral symmetry is expected to show up by the parity doubling of all hadronic states, i.e., the proton with $j^p = 1/2^+$ would have a $1/2^-$ partner(the Wigner-Weyl manifestation of the symmetry). Clearly this is not the case. This indicates that the symmetry is spontaneously hidden (often stated as spontaneously broken) and is manifested in the Nambu-Goldstone mode; parity violation occurs through the appearance of a massless pseudo scalar (0^-) meson. The opposite parity partner of the proton is a proton and a "massless pion".

There are profound consequences of spontaneous chiral symmetry hiding which are subject to experimental tests. In the SU(2) version of the picture the up and down quark masses are considered small and the three π mesons are the Nambu-Goldstone Bosons. In the SU(3) version the up, down, and strange quark masses are considered small and there are eight Nambu- Goldstone Bosons ($\pi^{\pm,0}, \eta, K^{0,\pm}, \bar{K}^0$). Below the chiral symmetry

breaking scale $\Lambda_x \simeq 1$ GeV all of the lightest hadrons are Nambu-Goldstone Bosons with the pions $\simeq 140$ MeV, the $\eta \simeq 547$ MeV and the Kaons $\simeq 496$ MeV.⁸ Clearly these masses are not zero, due to the explicit chiral symmetry breaking term L_m in the QCD Lagrangian. The lowest order estimate for the pion mass $m_\pi^2 = B_0(m_u + m_d)$ (Gell-Mann, Oakes, Renner relation) where B_0 is proportional to the scalar quark vacuum condensate $\langle 0 | \bar{q}q | 0 \rangle$ where q represents up or down quarks. This is an order parameter of QCD which mixes left and right handed states. From this formula one can see that $m_\pi \rightarrow 0$ in the chiral limit $m_q \rightarrow 0$. This formula for m_π represents the strong but not the electromagnetic interaction contribution. The experimentally observed mass difference $m_{\pi^\pm} - m_{\pi^0} = 4.59$ MeV⁸ is almost purely electromagnetic in origin. Since the lightest hadron is the π^0 meson its primary decay mode is $\pi^0 \rightarrow \gamma\gamma$. This allows us to perform a precision test of the predictions of the QCD axial anomaly which is the principal mechanism for this decay⁵ (see Sec.4).

The formulas for the masses of the K and η mesons contain the strange quark mass m_s . From the masses of these mesons (subtracting the electromagnetic contribution) the ratios of the light quark masses can be accurately obtained. If in addition QCD sum rules are also invoked the absolute values of $m_u = 5.1 \pm 0.9$, $m_d = 9.3 \pm 1.4$, $m_s = 175 \pm 25$ MeV have been obtained.⁹ Since the quarks are confined these absolute values are quoted in the $\bar{M}\bar{S}$ scheme at a scale of 1 GeV^a. It should be mentioned that there are other empirical and lattice values in the literature (see⁸ for a summary) indicating that the absolute values might change in the future. However the ratios are more accurately determined and are less likely to change significantly. The large strange quark mass compared to the up and down quark comes from the fact that the kaon and η are much more massive than the pion. Physically this means that the most accurate tests of chiral dynamics are in the pion sector. The fact that all of the up and down quark masses differ by almost a factor of two means that there is strong isospin (SU(2)) breaking in addition to electromagnetic effects.¹⁰ However since both of these masses are small the magnitude of this will be typically $\leq 1\%$ ¹¹ [Meissner]^b. The pseudoscalar η' meson with a mass of $\simeq 958$ MeV is very interesting. In the large N_c (number of colors) limit it would be the

^aIn QCD the coupling constant α_s and quark masses are scale and renormalization scheme dependent (see e.g. the QCD section of the particle data book⁸). It is customary to us the "modified minimum subtraction scheme" $\bar{M}\bar{S}$, to quote the value of α_s at the mass of the Z meson, and the quark masses at a scale of 1 or 2 GeV.

^breferences to talks at this meeting will be presented in brackets

ninth Nambu-Goldstone Boson. Its large mass is due to the QCD axial anomaly⁵ and therefore has a large component which does not vanish in the chiral limit.

The effective field theory that utilizes the concepts of spontaneously hidden chiral symmetry is called chiral perturbation theory (ChPT)^c. This is an effective (low energy) theory of QCD in which the quark and gluon fields are replaced by a set of fields $U(x)$ describing the degrees of freedom of the observed hadrons. For the Nambu-Goldstone Boson sector this is usually taken to be of the non-linear exponential form $U(x) = \exp[i\phi(x)/F_\pi]$ where F_π is the pion decay constant $\simeq 92$ MeV and ϕ represents the Nambu-Goldstone fields, a 2×2 matrix for the pion fields if we assume only that the up and down quarks are active, and a 3×3 matrix representing pion, η , and Kaon fields when we take the strange quark into account. The Lagrangian of QCD is replaced by an effective Lagrangian, which only involves the field $U(x)$, and even powers of its derivatives $L_{QCD} \rightarrow L_{eff}(U, \partial U, \partial^2 U, \dots) = L_{eff}^2 + L_{eff}^4 + L_{eff}^6 + \dots$ where the superscript n on L_{eff}^n represents the number of derivatives. The form of the terms are fully determined by the requirements of chiral symmetry. However the magnitudes of the terms are not determined by the symmetries and must be determined empirically or on the lattice. These are in reasonable agreement with model estimates^{7,14} which shows that the physics is understood. For the $SU(2)$ case the lowest ($n=2$) term is: $L_{eff}^2 = (F_\pi^2/4)[\text{tr}\{\partial_\mu U^\dagger \partial^\mu U\} + m_\pi^2 \text{tr}\{U + U^\dagger\}]$ which contains the well known pion decay constant and mass. The derivative term predicts that Nambu-Goldstone Bosons are emitted and absorbed in p waves and have no interaction as the momentum $\rightarrow 0$ in accordance with Goldstone's theorem. The mass term explicitly breaks chiral symmetry and causes a small interaction at zero momentum.

ChPT represents a systematic expansion with definite counting rules which are governed by the order which one chooses to work. The predictions are expansions in the Nambu-Goldstone Boson masses and momenta. To converge they must be small compared to the chiral symmetry breaking scale $\Lambda_x = 4\pi F_\pi \simeq 1$ GeV. They must also be in a region below any resonances or branch cuts. In πN scattering the energies must be significantly below the Δ resonance unless it is included as a dynamical degree of freedom in the calculations [Pascalutsa]. In their domain of validity they represent the predictions of QCD subject to the errors which are imposed by uncertainties in the low energy constants and by the neglect of higher

^cFor an introduction to ChPT see^{5,12} and for more complete reviews see^{1-3,13,14}

order terms. As such they are worthy of great experimental effort in order to check them. Any discrepancy which is significantly larger than the combined experimental and theoretical errors must be taken seriously!

2. Chiral Dynamics Phenomena and Experiments

Following this brief introduction to the basic ideas of spontaneous chiral symmetry hiding in QCD and ChPT the phenomena that are associated with this subject and the associated experimental possibilities will be outlined.

- Nambu-Goldstone Bosons at Low Energies
interactions: $\pi - \pi, \pi - K, \pi - \eta, \pi - \eta', K - \eta, \dots$
properties: RMS radii, polarizabilities
electromagnetic and hadronic decays: $\pi^0, \eta, \eta' \rightarrow \gamma\gamma,$
 $\gamma\gamma \rightarrow \pi\pi, \eta\eta, \eta \rightarrow \pi\pi\gamma, \eta \rightarrow 3\pi, \dots$
leptonic and semi-leptonic decays: $\pi, K \rightarrow e\nu\gamma, K^+ \rightarrow \pi^+ l\nu_l \dots$
- Nambu-Goldstone Boson-hadron scattering: $\pi - N, K - N, \dots$
- photo and electro-production of Nambu-Goldstone Bosons:
 $\gamma^* N \rightarrow \pi N, K\Lambda, \gamma^* \pi \rightarrow \pi\pi \dots$
- Hadron structure at low Q^2
Nucleon EM, axial, strange form factors:
RMS radii, magnetic moments
quadrupole amplitudes in $\gamma^* N \rightarrow \Delta$
Electric and magnetic polarizabilities, $\pi N - \sigma$ term
- long range part of N-N interaction. nuclear physics at low energies, nuclear astrophysics

This incomplete list shows the broad range of phenomena included in chiral dynamics. In this short presentation it is only possible to discuss a small fraction of these topics. The most pristine testing grounds for chiral dynamics is in the Nambu-Goldstone Boson section and $\pi - \pi$ scattering is the best case, both theoretically and experimentally. However experiments are difficult since precision is vital and there are no free pion targets. The best experimental method has been to study the final state interactions in $K \rightarrow \pi\pi l\nu$ and more recently by the cusp in $K \rightarrow 3\pi$. Since this subject was extensively covered in this workshop [Leutwyler, Goy-Lopez, Pelaez, Bedaque] I will say only that it is still very interesting and evolving. More open is the study of $\pi - K$ interactions for which values of the scattering lengths have been extracted from higher energy data using dispersion theory¹⁵ based on data from the $KN \rightarrow \pi KN$ reaction. Lower energy data has

been taken in the decay $D^+ \rightarrow \pi^- K^+ \mu^+ \nu$ from the FOCUS collaboration at Fermilab,¹⁶ but have not yet been incorporated into this analysis. As far as I know, there are no data on the interactions with the η or η' ; the latter is particularly interesting since it is a Nambu-Goldstone Boson in the large N_c limit and it is not clear how different its dynamics (e.g. scattering lengths) will be from, say, the η .

The polarizability of the pion has proven to be difficult to measure (for a summary see¹⁷ [Walcher, Kashevarov]). A recent experiment at Mainz¹⁸ is in serious disagreement with the result extracted from $e^+e^- \rightarrow \gamma\gamma \rightarrow \pi^+\pi^-$ experiments.¹⁹ In my view this is a potentially serious situation which urgently needs additional experimental effort. I think that an improvement in the accuracy of the e^+e^- experiments is needed since the sensitivity to the pion polarizability is not large. It would also be highly desirable to perform a modern radiative Primakoff experiment ($\pi^\pm\gamma \rightarrow \pi^\pm\gamma$ with pion beams).

The phenomena that are associated with the πN system are at the heart of nuclear physics. The π meson has a special role in the universe. The exchange of pions between nucleons (Yukawa interaction) is the long range part of the nucleon-nucleon potential, and governs low energy nuclear interactions and stellar formation. Indeed the effective theory of few nucleon systems[Nogga, Hahnhart] has become an integral part of chiral dynamics and of these workshops. The pion cloud which surrounds hadrons plays a major role in their structure, e.g. their form factors and polarizabilities[McGovern, Miskimen]. The Δ resonance (the first excited state of the nucleon) plays a central role in πN dynamics, a topic discussed below.

The Nambu-Goldstone Boson- Fermion sector is more difficult theoretically (compared to the purely Nambu-Goldstone Boson physics) but parts of it, e.g. πN physics, including low energy electromagnetic meson production, are much more easily accessible experimentally which has lead to extensive and accurate experimental data. This does not mean that all problems are solved. For example there is an old open problem that was not even discussed at this workshop, namely the value of the $\pi N - \sigma$ term. Generally the interpretation of this leads to a greater than 20% contribution of the strange quark to the nucleon mass. Yet, as we learn from parity violating electron scattering [Michaels], the strangeness magnetic moment is close to zero. There is no simple connection between these quantities since they are the expectation values of different operators. However, the fact that one is large and the other is small, needs explanation.

3. Pion-Nucleon Interactions and Electromagnetic Pion Production

In this and the next section I shall give a few specific examples to illustrate some of the specific applications of chiral dynamics. From the large number of possibilities I have chosen ones that I have worked on, and are close to my heart.

The πN interaction in momentum space = $g_{\pi N} \vec{\sigma} \cdot \vec{p}_\pi$ where $\vec{\sigma}$ is the nucleon spin. In accordance with Goldstone's theorem, this interaction $\rightarrow 0$ as the pion momentum $\rightarrow 0$. Furthermore $g_{\pi N}$ can be computed from the Goldberger-Treiman relation⁵ and chiral corrections,²⁰ and is accurate to the few % level. The πN interaction is very weak in the s wave and strong in the p wave which leads to the Δ resonance, the tensor force between nucleons, and to long range non-spherical virtual pionic contributions to hadronic structure. For illustrative purposes consider the lowest order ChPT calculation $O(p^2)$ for $a(\pi, h)$, the s wave π hadron scattering length; $a^I(\pi, h) = -\vec{I}_\pi \cdot \vec{I}_h m_\pi / (\Lambda_x F_\pi)$ where $\vec{I} = \vec{I}_\pi + \vec{I}_h$ is the total isospin, and I_π , and I_h are the isospin of the pion and hadron respectively, F_π is the pion decay constant, and $\Lambda_x = 4\pi F_\pi \simeq 1$ GeV is the chiral symmetry breaking scale.²¹ Note that $a(\pi, h) \rightarrow 0$ in the chiral limit $m_\pi \rightarrow 0$ as it must to obey Goldstone's theorem. Also note that $a(\pi, h) \simeq 1/\Lambda_x \simeq 0.1$ fm, which is small compared to a typical strong interaction scattering length of $\simeq 1$ fm. This small scattering length is obtained from the explicit chiral symmetry breaking due to the finite quark masses. The predictions of ChPT for πN scattering lengths have been verified in detail in a beautiful series of experiments on pionic hydrogen and deuterium at PSI;²² this includes the isospin breaking due to the difference in $m_d - m_u$ mentioned previously [Meissner].

Low energy electromagnetic production of Goldstone Bosons is as fundamental as Goldstone Boson scattering for two reasons: 1) the production amplitudes vanish in the chiral limit (as in scattering); and 2) the phase of the production amplitude is linked to scattering in the final state by unitarity or final state interaction (Fermi- Watson) theorem suitably modified to take the up, down quark masses into account.²³ First consider the low energy limit of the electric dipole E_{0+} for s wave photo- pion production:²⁴

$$\begin{aligned}
 E_{0+}(\gamma p \rightarrow \pi^0 p) &= -D_0 \mu (1 + O(\mu) + \dots) \rightarrow 0 \\
 E_{0+}(\gamma p \rightarrow \pi^+ n) &= \sqrt{2} D_0 / (1 + \mu + \dots)^{3/2} \rightarrow \sqrt{2} D_0 \\
 \mu &= m_\pi / M \rightarrow 0 \\
 D_0 &= e \cdot g_{\pi N} / 8\pi M = 24 \cdot 10^{-3} (1/m_\pi)
 \end{aligned}
 \tag{1}$$

where M is the nucleon mass and the right arrow denotes the chiral limit ($m_u, m_d, m_\pi \rightarrow 0$). Eq. 1 shows that for neutral pion production the amplitude vanishes in the chiral limit. For charged pion production, there is a different low energy theorem.²⁴ Therefore the amplitude that is most sensitive to explicit chiral symmetry breaking is neutral pion production and most of the modern experiments have concentrated on this channel. In general, ChPT to one loop calculated in the heavy Fermion approximation, has been highly successful in calculating the observed cross sections and linearly polarized photon asymmetry.²⁴

The application of these ideas to data from low energy πN scattering and electromagnetic pion production from the nucleon is instructive. The left panel of Fig.1 shows the shape of the Δ resonance from fits to the total cross sections for π^+p (scaled) scattering and for the $\gamma p \rightarrow \pi^0 p, \pi^+ n$ reactions versus W (the center of mass energy).²⁵ All of these reactions have a strong Δ resonance. The π^+p and $\gamma p \rightarrow \pi^0 p$ reactions have small cross sections near threshold and therefore clearly show the Δ resonance without any interference (the small shift between them is due to the mass difference of the Δ^0 and Δ^+). Indeed these cross sections are text book example of an isolated resonance. Although not usually mentioned in text books it is the combination of a strong resonance and a small cross section at threshold that produces this beautiful example (as predicted by chiral dynamics)! In the case of the $\gamma p \rightarrow \pi^+ n$ reaction there is strong s wave production starting at threshold due to the Kroll-Ruderman low energy theorem (see Eq.1. In this case the Δ resonance curve is superimposed on the strong s wave amplitude and looks quite different!

The photo and electro-pion $\gamma^* p \rightarrow \Delta$ reactions have been extensively used to study non-spherical amplitudes (shape) in the nucleon and Δ structure.²⁸ This is studied by measuring the electric and Coulomb quadrupole amplitudes (E2,C2) in the predominantly magnetic dipole, quark spin flip (M1) amplitude. At low Q^2 the non-spherical pion cloud is a major contributor to this (for a review see²⁸). Recently there have been chiral calculations of this process [Pascalutsa]. The right panel of Fig.1 shows our best estimate of the difference between the electro-excitation Δ for the spherical case (the relatively flat grey band) and the fit to the Bates data for the transverse-longitudinal interference cross section σ_{LT} ²⁶ which shows the C2 magnitude which is primarily due to the pion cloud [Stave].^{27,28} The evolution of the Coulomb quadrupole amplitude with Q^2 indicates that the quark models do not agree with experiment, but that models with pionic degrees of freedom do, demonstrating that the crucial ingredient in the

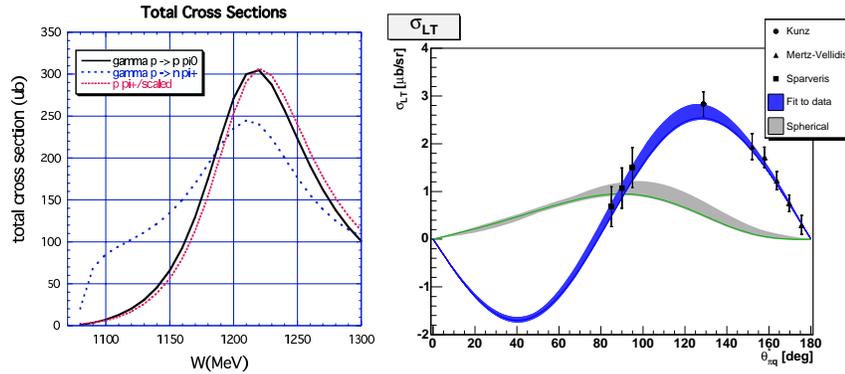


Fig. 1. Left panel: The shape of the Δ resonance from fits to the total cross sections for π^+p (scaled solid curve) scattering and for the $\gamma p \rightarrow \pi^0 p$ (short red dots), and $\gamma p \rightarrow \pi^+ n$ reactions (blue dotted curve which is larger at low W) versus W , the center of mass energy. The curves represent fits to the data.²⁵ Right panel: σ_{LT} from the $ep \rightarrow e' \pi^0 p$ reaction at $Q^2 = 0.126 GeV^2$, $W = 1232$ MeV (see text). The blue curve is fit to the data²⁶ and the relatively flat grey curve shows the calculation for the spherical case, i.e. when the quadrupole transition amplitudes are set to zero.^{27,28}

non-spherical amplitude at long range is the pion cloud [Stave].

A great deal of effort has gone into the study of the near threshold $\gamma p \rightarrow \pi^0 p$ reaction experimentally at Mainz²⁹ and Saskatoon³⁰ and with ChPT calculations.²⁴ In addition we are planning to conduct future experiments at HI γ S, a new photon source being constructed at Duke [Weller]. These experiments will have full photon and target polarization and will be a significant extension of the results we have at present. The unpolarized cross sections were accurately measured despite their small size and the results from Mainz and Saskatoon are in reasonable agreement. The p wave amplitudes tend to dominate even close to threshold. The real part of the s wave electric dipole amplitude ReE_{0+} is extracted from the data using the interference between s and p waves which goes as $\cos(\theta_\pi)$ in the differential cross section and leads to larger errors. The results for ReE_{0+} versus photon energy are plotted in the left panel of Fig. 2. There is reasonable agreement between the Mainz and Saskatoon points as well as with ChPT²⁴ and the unitary model calculations.²³ The sharp downturn in ReE_{0+} between the threshold at 144.7 MeV and the $\pi^+ n$ threshold at 151.4 MeV is due to a unitary cusp caused by the interference between the $\gamma p \rightarrow \pi^0 p$ and $\gamma p \rightarrow \pi^+ n$ channels. The magnitude of the cusp is $\beta = ReE_{0+}(\gamma p \rightarrow \pi^+ n) \cdot a_{cex}(\pi^+ n \rightarrow \pi^0 p)$ which is measured to an accu-

racy of $\simeq 30\%$ from the data shown. The reason for this accuracy limitation is due to the fact that the ReE_{0+} is a sum of a smooth and cusp functions and the smooth function is not known precisely.²³ Therefore it is important to measure ImE_{0+} which starts from close to zero at the π^+n threshold energy and rises rapidly as βp_{π^+} . This makes the extraction of β as accurate as the measured asymmetry for π^0 photoproduction from a polarized target normal to the reaction plane. The estimated error for such an experiment running at HI γ S for $\simeq 400$ hours of anticipated operation of the accelerator is presented in the right panel of Fig.2. This experiment, along with an independent measurement of the $\gamma p \rightarrow \pi^+n$ cross section will allow us to extract β at the few % level and measure the charge exchange scattering length $a_{cex}(\pi^+n \rightarrow \pi^0p)$ for the first time. We will be able to compare this to the measured value of $a_{cex}(\pi^-p \rightarrow \pi^0n)$ ²² as an isospin conservation test. This illustrates the power of photopion reaction studies with transversely polarized targets to measure πN phase shifts in completely neutral charge channels which are not accessible to pion beam experiments! This is potentially valuable to help pin down experimentally the value of the $\pi N - \sigma$ term which has had a long, difficult measurement history.

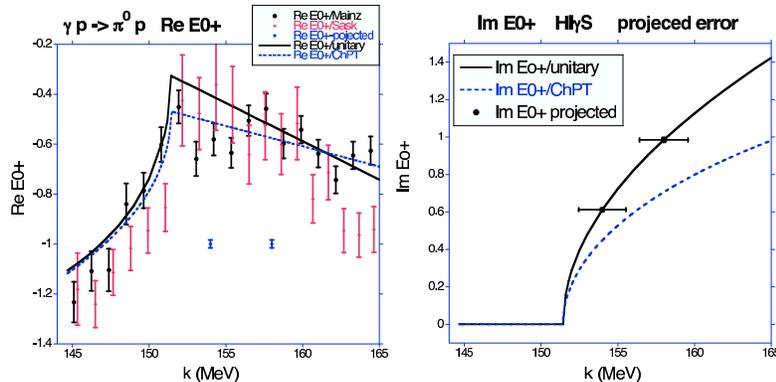


Fig. 2. The $\gamma p \rightarrow \pi^0 p$ Reaction. Left panel: ReE_{0+} versus photon energy. The data points are from Mainz²⁹ and Saskatoon.³⁰ The curves are from ChPT²⁴ and a unitary fit to the data.²³ The two projected points from HI γ S are plotted at an arbitrary value ($ReE_{0+} = -1$) to show the anticipated errors. Right panel: $Im E_{0+}$ versus photon energy. The curves are the same as in the left panel and the projected HI γ S points are arbitrarily plotted on the unitary curve. There are no experimental points (see text).

ChPT has been extremely successful in predicting the cross sections and the linearly polarized photon asymmetry in the $\gamma p \rightarrow \pi^0 p$ reaction. However

I would like to point out a significant discrepancy with the $ep \rightarrow e' p \pi^0$ reaction data at $Q^2 = 0.05 \text{ GeV}^2$ taken at Mainz³¹ shown in Fig.3. It can be seen that the ChPT calculations³² do not agree with the data although the DMT dynamical model does.³³ This discrepancy is a potentially serious problem which needs to be resolved!

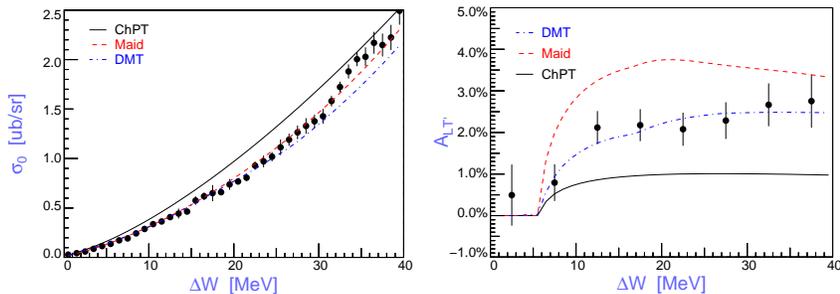


Fig. 3. Cross Section (Left panel) and LT' Asymmetry (right panel) for the $ep \rightarrow e' p \pi^0$ Reaction at $Q^2 = 0.05 \text{ GeV}^2$ versus dW , the center of mass energy above threshold.³¹ See text for discussion.

4. The $\pi^0 \rightarrow \gamma\gamma$ Decay Width and the QCD Axial Anomaly

As the final special topic I would like to discuss a test of the axial anomaly by an accurate measurement of the π^0 lifetime. As was discussed in the introduction, due to the spontaneous breaking of chiral symmetry, the π^0 is the lightest hadron and its primary decay mode is $\pi^0 \rightarrow \gamma\gamma$. This decay rate is exactly predicted in the chiral limit by the QCD axial anomaly. As is quoted in most textbooks on QCD (see e.g.⁵) this prediction is in agreement with the average in the particle data book⁸ which has a error $\simeq 10\%$. However this oversimplifies the experimental situation which is shown in Fig.4. In my opinion, almost all of the errors quoted in the literature are underestimates. This is indicated by the spread in the experimental values. Also at issue are the chiral corrections to the decay rate. These have been worked out to next to leading order. They primarily involve $\pi - \eta, \eta'$ mixing which is isospin breaking and therefore proportional to $m_d - m_u$; they increase the predicted decay width by $4 \pm 1\%$.³⁴

This experiment has been performed by the Primex collaboration at JLab and the data analysis is in the final stages [McNulty]. The experiment measures the photo-production of π^0 mesons from C and Pb at an average

photon energy $\simeq 5.2$ GeV and has the goal of achieving an accuracy of a few %. It is the first Primakoff measurement to use a tagged photon beam. Preliminary results are shown in Fig.4. The large forward peak is due to the Primakoff effect which is the production of π^0 's in the Coulomb field of the target. The larger peak at a few degrees in C is due to coherent nuclear production and there is a small quantum interference amplitude. The fits to these processes are shown. For the Pb target (not shown) the nuclear coherent peak is small compared to the Primakoff peak. This is due to final state absorption causing the coherent nuclear cross section to scale $\simeq A$, while the Primakoff cross section scales $\simeq Z^2$. Therefore the relative coherent to Primakoff peak decreases with heavier targets. As can be seen the preliminary data look good and our collaboration expects to release preliminary lifetime results in the next half year.

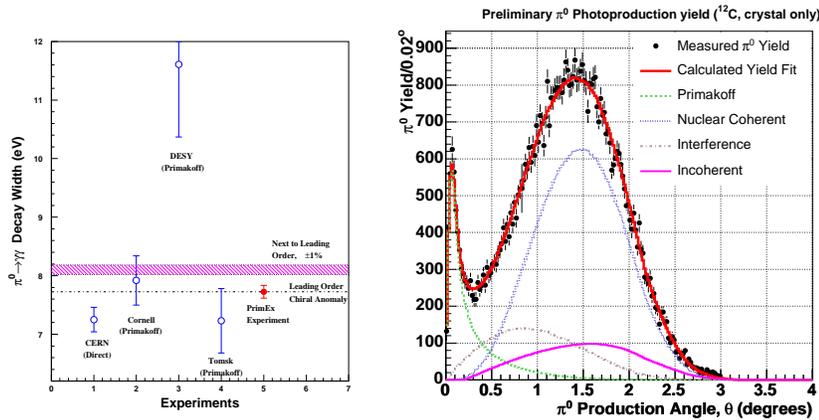


Fig. 4. Left panel: the $\pi^0 \rightarrow \gamma\gamma$ decay width in eV. These include the experimental points,⁸ the projected error of the Primex collaboration (arbitrarily plotted to agree with the predictions of the axial anomaly), and the next to leading order chiral correction.³⁴ Right panel: Preliminary yield and fit for the Primakoff effect on Carbon versus pion angle with the individual contributions to the total yield exhibited (see text for discussion).

5. Conclusions

It is clear that chiral physics includes an impressive array of reactions and particle properties. The general concepts and detailed calculations of ChPT are generally verified for the Nambu-Goldstone meson sector where they

have been tested. The physics is more complicated when Fermions are also included. This sector is more closely related to the observable world, e.g. the properties of nucleons, and the formation of the stars. In this sector there are many areas of good agreement between ChPT and experiment but there are also a few outstanding problems

Finally here is a short wish list that I would like to see granted by CD2009:

- measurements of the pion polarizabilities by different techniques to address the existing discrepancy
- further calculations and measurements of the $ep \rightarrow e' p \pi^0$ reaction to resolve the existing discrepancy
- accurate measurements of the decay $\pi^0, \eta, \eta' \rightarrow \gamma\gamma$ decay widths
- further isospin tests in the πN scattering and $\gamma N \rightarrow \pi N$
- progress on the $\pi N - \sigma$ term
- further calculations and experiments on the nature of η' Boson; what does it mean physically that this is a Nambu-Goldstone Boson in the large N_c limit?
- more data on the interactions between the heavier Nambu-Goldstone Bosons

It was a pleasure for me to experience this workshop that was so stimulating and well organized. Personally I learned a great deal in a collegial and enthusiastic atmosphere. I would like to thank that organizers and Duke University for their wonderful organization and hospitality. I would also like to thank M. Kohl and D. McNulty for their careful reading of this manuscript. This work has been supported in part by the U.S. Department of Energy under Grant No. DEFG02-94ER40818.

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