Experimental Chiral Dynamics

A.M. Bernstein
Hadronic and Electroweak Physics at MIT
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- Spontaneous Chiral symmetry hiding
  Nambu-Goldstone Bosons $\Rightarrow$ ChPT $\Rightarrow$ Low energy theorems

Experimental Tests

- $\pi$ hadron scattering
- photo pion production
- $\Delta$ resonance shape and low energy theorems
- $\pi^0 \rightarrow \gamma \gamma$ : Axial anomaly $\Rightarrow$ PrimEx

- Open problems
Chiral Dynamics Workshops

• Equal Mixture of Theory and Experiment
• Working groups

Previous Workshops
• MIT 1994
• Mainz 1997
• Jefferson Lab 2000
• Bonn 2003

Duke 2006 covered a wide range of topics
• Goldstone Boson Dynamics
• Hadron Structure and Meson-Baryon Interactions
• Few Body Physics
Chirality (handedness) left handed $s=1/2$ particle

$\sigma \leftrightarrow p \rightarrow P_L = 1/2 \left(1 + \gamma^5 \right)$

for massless Fermions chirality is a Lorentz invariant

chiral symmetry
For massless quarks the QCD Lagrangian can be written as separate left and right handed terms which can transform differently.

The chiral symmetry is spontaneously broken (hidden) parity doublets are not seen

however the symmetry is not lost but re-appears as massless pseudoscalar mesons

degenerate $N\left(1/2^+\right) \rightarrow N(1/2^+)\pi(0^-)$
\[ \pi^2 = B(m_u + m_d) \approx (140 \text{ MeV})^2 \rightarrow 0 \]

\[ m_u \approx 5 \text{ MeV} \quad m_d \approx 9 \text{ MeV} \]

\[ m_s \approx 140 \text{ MeV} \]
\[ L_{\text{QCD}} = L_0 + L_m \]

chiral symmetry is explicitly broken by quark mass effects

Nambu-Goldstone Boson acquire mass

\[ L_m = A(m_u + m_d) + B(m_u - m_d) \]
\[ m_d / m_u \approx 1.8 \]

isospin broken by strong and EM interaction

strong int. effect \( \approx (m_d - m_u) / \Lambda_{(QCD)} \approx 2\% \)
- **Low Energy $\pi$ -Hadron Scattering**
  - Pure Nambu-Goldstone Boson: $a(\pi h) = 0$
  - Strong Interactions: $a(\pi h) \approx 1/m_{\pi} \approx 1$ fm

**PCAC Calculation by Weinberg (1966)**
- Lowest order ChPT Calculation

$$a^I(\pi h) = - I_\pi \cdot I_h \quad m_{\pi} / (\Lambda F_{\pi}) \approx 1/\Lambda \approx 0.1 \text{ fm}$$
$$\rightarrow 0 \quad \text{as} \quad m_{\pi} \rightarrow 0$$
$$I = I_\pi + I_h$$

$\Lambda$ = Chiral Sym. Breaking Scale $= 4 \pi F_{\pi} \approx 1$ GeV

Expect Chiral Corrections of Order $(m_{\pi}/\Lambda)^2 \approx 0.02$

**Threshold $\gamma^* N \rightarrow \pi N$**
- S and P wave production amplitudes
- There are ChPT Formulas [Bernard, Meissner, Kaiser]

The Chiral Limit for S Wave Amplitudes

$$A(\gamma^* N \rightarrow \pi^0 N) \rightarrow 0$$

$$A(\gamma^* N \rightarrow \pi^\pm N') \neq 0$$

and large (Kroll-Ruderman theorem)
Chiral Dynamics

- Properties, Interactions, decays of Nambu-Goldstone Bosons (G) at Low Energies
- G-G, G-h scattering (h is any hadron)
- Form factors at low $Q^2$ (RMS radii)
  $\gamma^*N \rightarrow \Delta$
- Electric and magnetic polarizeabilites
- semi-leptonic decay rates
- special role of the $\pi$ meson
  long range part of N-N interaction
  nuclear physics, astrophysics
  pion cloud of hadrons

The experiments require a wide range of techniques
Leutwyler-CD2006-s wave- $a(\pi\pi)$

Exp: NA48-CERN  cusp in $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$

E865-BNL  $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$

![Graph showing the results of the calculations and comparisons between theoretical predictions and experimental data. The graph plots $a_0$ against $\pi\pi$ coupling constants, with various theoretical predictions and experimental data points marked.]
$a(\pi K)$: Mossallam

data from Focus Collaboration: Fermilab

$D^+ \rightarrow K^- \pi^+ \mu^+ \nu$

Figure 14: Standard error ellipse for the $S$-wave scattering lengths obtained from solvin, RS equations with boundary conditions. The corresponding ellipse in the ChPT calculation $O(p^4)$ and the current-algebra result are also plotted.
Goldberger-Treiman
Exact in the chiral limit

\[ M_N g_A(0) = F_\pi g_{\pi NN}(0) \]

\[ 1 - \frac{M g_A(0)}{F_\pi g_{\pi NN}(m^2_\pi)} : \]

\[ g^2_{\pi NN}/4\pi = 14.5 \]

\[ g^2_{\pi NN}/4\pi = 13.6 \]

ChPT O(p^3)
Goity.....PL(1999)
• $\pi N$ Interaction $= \ g_{\pi N} \ \vec{\sigma} \cdot \vec{p} \rightarrow 0$ as $p \rightarrow 0$.
  this is p wave pion emission and absorption by hadrons

• a large coupling constant $g_{\pi N}$ is predicted by the Goldberger-Trieman relation $g_{\pi N} = M_N g_A / F_\pi$

• $V_{NN} = g_{\pi N}^2 \ \vec{\sigma}_1 \cdot \vec{p} \ \left[ \frac{1}{p^2 + m_\pi^2} \right] \ \vec{\sigma}_2 \cdot \vec{p}$
  this is the non-central tensor force
\( \Delta(1232\text{MeV}) \) Resonance: Total Cross Section

- **gamma p -> p pi0**
- **p pi+/scaled**

**Graph Details**
- **Y-axis**: total cross section (ub)
- **X-axis**: W(MeV)
- **Plot Range**:
  - X-axis: 1100 to 1300 MeV
  - Y-axis: 0 to 350 ub
\[ \tilde{N}(\vec{\gamma}, \pi), \pi N \text{ Reactions} \]

**Previous Experiments:**
Probing spontaneous chiral symmetry hiding, quark mass effects \( m_d + m_u \)

- verify ChPT, including unitary cusp
  - start on linear polarized photon asymmetry
  - s wave photo-production amplitudes \( \text{Re } E_{0+} \)
  - \( \rightarrow 0 \) in the chiral limit, \( m_q \rightarrow 0, m_\pi \rightarrow 0 \)

**Future Experiments**

- utilize polarized photon beams and targets
- measure all multipoles including \( \text{Im } E_{0+} \)
- check IS conservation \( \approx 1\% \)
- measure \( a_{cex}(\pi^+ n \rightarrow \pi^0 p) \)
Experimental setup $\gamma + p \rightarrow p + \pi^0$

- **linearly polarized photons:**
  - $\vec{E} \perp$ and $\parallel$ to TAPS
  - $\rightarrow N^\perp$ and $N^\parallel$

- **Energies:**
  - $E_0 = 405$ MeV
  - $E_\gamma = E_0 - E_{e^-}$
  - $E_\gamma = 140 - 350$ MeV
  - $\Delta E_\gamma = 1$ MeV

- **Setup:**
  - TAPS - setup
  - Array of 504 BaF$_2$ - detectors

- **Forward wall with:**
  - 120 modules

- **Components:**
  - LH$_2$
  - $50$ cm
  - $\gamma$
  - tagging magnet
$\gamma \, p \rightarrow \pi^0 \, p \quad \text{Mainz data, ChPT}$
$\gamma p \rightarrow \pi^0 p$  Mainz data

ChPT: $O(q^4)$

$O(q^3)$
$\gamma p \rightarrow \pi^0 p$ polarized photon asymmetry

Sigma(90)

k(MeV)
Crystal Ball at MAMI

azimuthal $\phi$ dependence in $\gamma p \rightarrow p \pi^0$ with Crystal Ball CB

$$\frac{d\sigma}{d\Omega}(\Theta, \phi) = \frac{d\sigma}{d\Omega}(\Theta) \left( 1 - P_y \Sigma(\Theta) \cos(2\phi) \right)$$
Unitary Cusp  $\gamma p \rightarrow \pi^0 p$

$\beta = E_{0+}(\gamma p \rightarrow \pi^+ n) a_{cex}(\pi^0 p \leftrightarrow \pi^+ n)$

cusp sign and magnitude
$$\text{ep} \rightarrow \text{e}'p \pi^0$$  Mainz: A1, Merkel.....

M. Weiss thesis

$$\text{Im } E_{0+} \quad Q^2=0.05 \text{ GeV}^2$$
New Opportunities at H1γS
High Intensity γ Source at Duke

• $N_\gamma \approx 6 \cdot 10^6$ photons/sec (initial operation)

• $\Delta E_\gamma \approx 2\%$ (initial operation)

• perform $\gamma p \rightarrow \pi^0 p, \pi^+ n$ experiments with polarized photons and targets, single and double polarization observables

♦ Observe isospin breaking due to up, down quark mass difference ($m_d - m_u$)

• unitary cusp in $\gamma p \rightarrow \pi^0 p$
  
  measure $a(\pi^+ n \rightarrow \pi^0 p)$ charge exchange
Fig. 18. A diagram indicating the design of the Crystal Box and the locations of the associated detectors.
Anomalous Reactions

- An anomaly of QCD occurs when a multiplicative quantum number called intrinsic parity is violated [E.Witten, Nucl. Phys. B223, 422(1983)]

- \( IP = +1 \) for scalar, vector, ... particles
  \( IP = -1 \) for Pseudo-scalars, pseudovectors, ...

- \( \pi^0 \rightarrow \gamma \gamma \)
  \(-1 \rightarrow +1\)

- \( \gamma \pi \rightarrow \pi \pi \)
  \(-1 \rightarrow +1\)
\[ \pi^0 \rightarrow \gamma\gamma \] \textbf{Decay Rate in QCD}

- The prediction of the axial anomaly \( O(p^4) \) exact in the chiral limit \( m_u = m_d = m_\pi = 0 \)
  
  \[ A_{\gamma\gamma} = \frac{\alpha}{\pi f_\pi} \]
  
  \[ \Gamma(\pi^0 \rightarrow \gamma\gamma) = m_\pi^3 |A_{\gamma\gamma}|^2 / (64\pi) = 7.725 \text{eV} \]

- explicit chiral symmetry breaking corrections:
  
  \( m_{u,d,s} \neq 0 \)

  mixing of \((\pi, \eta, \eta')\) due to \( m_d - m_u \neq 0 \)

  \[ <\pi | \eta > \approx (m_d - m_u) / m_s \]

- ChPT calculations to \( O(p^6) \) and \( O(p^4 \times 1/N_c) \),
  
  including EM corrections increase \( \Gamma \) by 4.5% \( \Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10 \pm 0.08 \text{ eV} \)

  B. Ananthanarayan and B. Moussallam (2002)

  J. Goity, A.M.B., B. Holstein (2002)
Chiral correction
$\pi-\eta, \eta'$ mixing \sim (md-mu)

Projected error

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ World Data
First Primakoff exp to
Use tagged photons
Experiment Overview

- Tagged photons of energy 4.9 - 5.5 GeV were used to measure the absolute cross section of small angle $\pi^0$ photoproduction from the coulomb field of two nuclei ($^{12}C$ and $^{208}Pb$).

- The invariant mass and production angle of the pion were reconstructed by detecting the two $\pi^0$ decay photons in a highly segmented calorimeter centered on the beamline.

- The number of tagged photons reaching the target was calibrated using a Total Absorption Counter (TAC) and monitored with an $e^+e^-$ pair spectrometer.
Data Collection

- HyCal Calibration: “snake” scan before and after experiment (for gain alignment and energy calibration)
- Periodic TAC/luminosity runs—measure absolute tagging efficiency for photon flux determination
- Periodic Compton runs (to measure absolute Compton coss section)—used for systematic studies of experimental setup (detector alignment, $\pi^0$ yield normalization, and monitor HyCal gain drifts).
- $\pi^0$ photoproduction from $5\% \chi_0^12\text{C}$ and $^{208}\text{Pb}$ targets using $\sim 100\text{nA}$ e-beam current which generated $\sim 5\text{MHz}$ tagged photon rate.
- DAQ event readout triggered by HyCal total ADC sum in coincidence with tagger hodoscope hit (produced a rate of $\sim 1.5\text{kHz}$)
Primex: Preliminary

Primakoff peak

Nuclear coherent Supressed in Pb compared to C
Electric and magnetic polarizabilities

$\alpha(Q^2)$

$\beta(Q^2)$
<table>
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<tr>
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<th>Mean square electric polarizability radius $\langle r^2_{\text{charge}} \rangle$</th>
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<tbody>
<tr>
<td>Experiment</td>
<td>$2.16 \pm 0.31 \text{ fm}^2$, $0.757 \pm 0.014 \text{ fm}^2$</td>
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<tr>
<td>HBChPT</td>
<td>$1.7 \text{ fm}^2$, $0.717 \text{ fm}^2$</td>
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**Diagram:**

- **Polarizability**: $q$, $q_v$
- **Form factor**: $q_v$
Outlook: Spontaneous Chiral Symmetry Breaking
⇒ Nambu-Goldstone Bosons, quark Mass Effects
⇒ $m_d \neq m_u$ IS breaking
⇒ $m_d, m_u \neq m_s$ SU(3) breaking

• physics includes an impressive array of reactions, particle properties
• generally verified for meson sector $\pi, \eta, K$ (pions best)
• more complicated for GB-Fermions: $\pi-N, \gamma^* N \rightarrow \pi N, \gamma p \rightarrow \Lambda K^+$

Some experimental discrepancies
$\pi^+$ polarizability
$\gamma^* p \rightarrow \pi^0 p$ W, Q2 dependence
.....