Coherent Photoproduction of $\pi^0$-Mesons off Nuclei

- nuclear mass distributions -

B. Krusche, University of Basel, Switzerland

Introduction & Motivation

Experiments

Photoproduction of $\pi^0$-Mesons

- PWIA, FSI, DWIA and in-medium effects
- coherent production and rms-radii
- coherent production and dms-radii (Helm-model)

Summary

Other coherent production channels (?)
Shape and size of nuclei - nuclear form factors

- charge distribution of nuclei studied by different tools with high precision (e.g. $^{208}$Pb charge rms radius accuracy $< 0.001$ fm)
  - electron scattering experiments
  - myonic atoms
  - ...

- model predictions for ‘neutron skin’

- ... but matter distributions not well known (e.g. $^{208}$Pb rms neutron radius accuracy $\approx 0.2$ fm)
  - hadron induced experiments (strong interaction):
    large cross section, but complicated interaction, ISI and FSI
  - weak interaction: small cross sections
  - alternative: photon induced coherent meson production
    in particular: coherent $\pi^O$-production in $\Delta$-resonance region

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
Photoproduction of mesons off nuclei - Overview

- **breakup (quasi-free)**
  \[ \gamma + A \rightarrow \pi^0 + A' + N + \ldots \]
  \[ \frac{d\sigma}{d\Omega} \propto \sum |A|^2 \times \ldots \]
  & nuclear effects & FSI & \ldots
  & in-medium properties of mesons & resonances
  & meson - nucleon interaction (FSI)...

- **coherent**
  \[ \gamma + A \rightarrow \pi^0 + A \]
  \[ \frac{d\sigma}{d\Omega} \propto |\sum A|^2 \times F^2(q^2) \times \ldots \]
  & nuclear effects & FSI & \ldots
  & nuclear form factors
  & \[\bigtriangleup\] in-medium properties....
  & spin/iso-spin filters
  & meson - nucleus bound states...

- **incoherent**
  \[ \gamma + A \rightarrow \pi^0 + A^* \]
  \[ \rightarrow \pi^0 + A + \gamma \]
  & transition form factors
  & \[\bigtriangleup\] in-medium properties....
  & spin/iso-spin selection
photoproduction of pions in the $\Delta(1232)$ range

$\gamma \pi^0$ channel: dominance of $\Delta(1232)$ excitation

$n\pi^+$ channel: $\Delta$ & background

**total cross sections**

- $\gamma p \rightarrow p\pi^0$
- $\gamma p \rightarrow n\pi^+$

**angular distributions** $\sim [5 - 3\cos^2(\Theta^*)]$
photo-excitation of the $\Delta(1232)$ resonance

- $\Delta$ elm. excitation: quark spin-flip
  M1 excitation of $3/2^+$ state ($M_{1^+}$)

- iso-spin decomposition
  \[ A(\gamma p \rightarrow \pi^0 p) = \sqrt{\frac{2}{3}} A^{V_3} + \sqrt{\frac{1}{3}} (A^{IV} - A^{IS}) \]
  \[ A(\gamma n \rightarrow \pi^0 n) = \sqrt{\frac{2}{3}} A^{V_3} + \sqrt{\frac{1}{3}} (A^{IV} + A^{IS}) \]

- decay via p-wave pion
  $\implies$ no change of nucleon spin orientation!

- only contribution from iso-spin changing $V_3$
  $\implies$ identical contribution from protons and neutrons!

only contribution from spin, iso-spin independent amplitude $\mathcal{F}_2$!
coherent $\pi^O$-photoproduction off nuclei in the $\Delta$-range

$$\gamma + A \rightarrow \pi^O + A$$

- coherent kinematics: two-body final state
  used to identify the reaction (‘missing energy’)
- most simple PWIA approximation:

$$\frac{d\sigma}{d\Omega}(PWIA) = \frac{s}{m_N^2} \times \frac{1}{2k^*} |F_2(E_{\gamma}^*, \Theta_{\pi}^*)|^2 \sin^2(\Theta_{\pi}^*) \times A^2 F^2(q)$$
importance of final state interaction - pion absorption

results from inclusive (quasi-free) pion photoproduction

- **A-scaling of cross sections** as function of kinetic energy $T$:
  \[ \sigma(A) \propto A^{\alpha(T)} \]

  - $\alpha \approx 1$: 'volume', no absorption
  - $\alpha \approx 2/3$: 'surface', strong absorption

- BUU transport model simulations: origin of observable (not absorbed) pions for $^{208}$Pb:
  (Giesen BUU, Mosel et al.)

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
**model for coherent production - fit to $^4$He($\gamma, \pi^0$)$^4$He**

- **DWIA calculation** (Drechsel et al., NPA 660 (1999))
  - PWIA amplitudes: Unitary Isobar Model,
    Drechsel et al., NPA 645 (1999)
  - DWIA: pion FSI from pion-nucleus elastic scattering amplitudes
  - $\triangle$ in-medium modification parametrized with $\triangle$ self-energy

$$
\frac{1}{W - M_{\triangle} + i\Gamma(W)/2} \quad \rightarrow \quad \frac{1}{W - M_{\triangle} + i\Gamma(W)/2 - \Sigma_{\triangle}}
$$

$$
\Sigma_{\triangle}(E_{\gamma}, q^2) = V(E_{\gamma})e^{-\beta q^2}
$$

- **fit results:** (data: F. Rambo et al., Nucl. Phys. A660 (1999) 69)

  - fit to data for coherent production from $^4$He:
    $\Re(V) \approx 20$ MeV, $\Im(V) = -20, ..., -55$ MeV
    $\rightarrow$ mass shifted upward by $\approx 20$ MeV
    $\rightarrow$ width increased by $\approx 40 - 110$ MeV

---

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
comparison to model for heavy nuclei

- **angular distributions:**
  - : PWIA
  - : DWIA
  - : DWIA, $\Sigma$$_\Delta$

- **total cross sections**

- good agreement up to $^{40}$Ca (still reasonable for Pb) with $\Sigma$$_\Delta$ taken from fit to $^4$He
  
  → saturation of $\Delta$-nuclear interaction

B.K. et al., PLB 526 (2002) 287

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
comparison PWIA versus full model

- influence of FSI effects (example: lead):

- effect on magnitude of cross section (momentum transfer dependent)
- shift of diffraction minima (more pronounced for higher orders)

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
summary of related experiments

- quasi-free and coherent $\pi^0$-production off the deuteron
  TAPS @ MAMI; B.K. et al., EPJA 6 (1999) 309

- coherent $\pi^0$-production off $^4\text{He}$
  TAPS @ MAMI; F. Rambo et al., NPA 660 (1999) 69

- coherent $\pi^0$-production off heavy nuclei
  TAPS @ MAMI; B.K. et al., PLB 526 (2002) 287

- quasi-free and inclusive $\pi^0$-production off heavy nuclei
  TAPS @ MAMI; B.K. et al., EPJA 22 (2004) 277

- nuclear mass form factors from coherent $\pi^0$-production
  TAPS @ MAMI; B.K., EPJA 26 (2005) 7

- incoherent $\pi^0$-production off $^{12}\text{C}$
  Crystal Ball/TAPS @ MAMI, C.M. Tarbert et al., PRL 100 (2008) 132301

- nuclear mass form factors from coherent $\pi^0$-production
  Crystal Ball/TAPS @ MAMI, D. Watts et al., in preparation

- coherent $\pi^0\eta$-production off $^2\text{H}$ and $^4\text{He}$
  Crystal Ball/TAPS @ MAMI, Crystal Barrel/TAPS @ ELSA; I. Jaegle, F. Pheron et al., in preparation

- coherent $\pi^0\eta$-production off heavy nuclei
  Crystal Ball/TAPS @ MAMI, Crystal Barrel/TAPS @ ELSA; I. Keshelashvili et al., under analysis
MAMI accelerator in Mainz

Mainz Microtron (MAMI)
continuous wave electron accelerator, max. beam energy 883

0. Stage: Linac (2.5 GHz, 3.45 MeV)

1.-3. Stage: Racetrack Microtrons:
- microbunches of 0.4 ns
- linear accelerator structures
- constant B field ⇒ varying radii (18, 51, 90 return cycles)
- very efficient acceleration and continuous mode
- high current (0.1 mA)

4. Stage: Harmonic Double Sided Microtron
maximum energy: 1.5 GeV
the TAPS detector

- electromagnetic calorimeter made of hexagonally shaped BaF$_2$-crystals
- 520 modules, 20 cm long, 12 radiation lengths, 5.9 cm inner circle
- good timing (FWHM ≈ 350 ps), possibility of pulse-shape analysis for particle identification, additional plastic veto detectors

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
recent $4\pi$-setups: Crystal Ball & Crystal Barrel with TAPS

- **Bonn ELSA accelerator:**
  - Crystal Barrel (CsI),
  - TAPS (BaF$_2$) forward wall,
  - inner detectors
  - $E_\gamma \leq 3.5$ GeV,
  - lin. pol.: available,
  - circ. pol.: available

- **Mainz MAMI accelerator:**
  - Crystal Ball (NaJ),
  - TAPS (BaF$_2$) forward wall,
  - inner detectors
  - $E_\gamma \leq 0.8$ (1.5) GeV,
  - lin. pol.: available,
  - circ. pol.: available

_B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009_
TAPS Crystal Ball - at MAMI

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
reaction identification

- $\pi^0$-mesons: invariant mass from $\pi^0 \rightarrow 2\gamma$ (clean in energy range of interest)
- coherent channel from reaction kinematics (‘missing energy’)
  - efficient against multiple pion production and breakup reactions
  - only partly efficient against nuclear excitations (incoherent reactions)

- invariant mass

- missing energy

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
coherent pion photoproduction in PWIA

- angular dist. $E_\gamma = 0.2 - 0.3$ GeV
- comparison to PWIA:

$$R_{PWIA} = \left(\frac{d\sigma}{d\Omega}\right)_A / \left[\left(\frac{d\sigma}{d\Omega}\right)_{PWIA} / F^2(q)\right]$$

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
**root-mean-square radii from FF slope**

- $r_{rms}$ from slope of FF for $q^2 \to 0$:
  
  $$F(q^2) = 1 - \frac{q^2}{6} r_{rms}^2 + \mathcal{O}(q^4)$$

- extract angular distribution
- extract FF in PWIA
- correct for finite resolution
- correct for DWIA effects
- fit polynomial

$$F(q^2) = \sum_{n=0}^{N} (-1)^n a_n q^{2n}$$

- extract rms-radius

$$r_{rms} = \sqrt{6a_1 / a_0}$$

- systematic checks: vary fit range and degree of polynomial

---

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
fits of form-factor slopes

$E = 200 - 245$ MeV

$E = 245 - 290$ MeV

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
results for rms-radii

- systematic effects from PWIA/DWIA, fit range, degree of polynomial:
- comparison to rms charge-radii:
  - correction of charge radii for finite proton rms radius:
    \[ r_{rms}^{pc} = \sqrt{(r_{rms}^{ch})^2 - (r_{rms}^p)^2} \]
- results:

<table>
<thead>
<tr>
<th>nucl.</th>
<th>( r_{rms} ,[\text{fm}] )</th>
<th>( r_{rms}^{pc} ,[\text{fm}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{12}\text{C})</td>
<td>2.28±0.10</td>
<td>2.32</td>
</tr>
<tr>
<td>(^{40}\text{Ca})</td>
<td>3.22±0.10</td>
<td>3.35</td>
</tr>
<tr>
<td>(^{93}\text{Nb})</td>
<td>3.96±0.10</td>
<td>4.22</td>
</tr>
<tr>
<td>(\text{nat},\text{Pb})</td>
<td>5.20±0.15</td>
<td>5.42</td>
</tr>
</tbody>
</table>

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
**diffraction radii in Helm-model**

- model for form-factor: product of hard sphere with Gaussian

\[ F_H = F_G \cdot F_{hs} = \exp\left(-\left(q\sigma\right)^2/2\right) \cdot \frac{3}{qR_d} j_1(qR_d) \]

- diffraction radii \( R_d \) from zeros of first order spherical Bessel function \( j_1 \)

- width \( \sigma \) of Gaussian from first maximum:

\[ \sigma^2 = \frac{2}{q_m^2} \ln \frac{3j_1(q_mR_d)}{q_mR_dF(q_m)} \]

- relation between root-mean-square and diffraction radii:

\[ r_{rms} = \sqrt{\frac{3}{5}} R_d \left(1 + 5 \left(\frac{\sigma}{R_d}\right)^2\right)^{1/2} \]

---

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
form factors in PWIA compared to Helm model

- form factors extracted in PWIA
- normalized by fitting slope to $F(q=0)=1$
- and plotting versus $qR_d$
- compared to hard sphere FF (black curve)
- and Helm model with $\sigma=0.75$
- and $R_d$ for Pb, Ca, C (blue, green, margenta curves)

- effect from surface thickness visible for carbon at low $q$
- effects from surface thickness and FSI cancel almost perfectly above first minimum and at larger $q$

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
nuclear mass radii from diffraction minima:

\[ \frac{d\sigma}{d\Omega} \left[ \mu b/sr \right] \]

\( \gamma \rightarrow \pi^0 \) Ca
\( E_\gamma = 260 - 350 \) MeV

\[ 12 \text{C} \quad R_d = 2.51 \pm 0.24 \quad \frac{R_d}{A^{1/3}} = 1.10 \pm 0.10 \quad \frac{R_d}{R_d^{charge}} = 1.03 \pm 0.10 \]

\[ 40 \text{Ca} \quad R_d = 3.68 \pm 0.10 \quad \frac{R_d}{A^{1/3}} = 1.08 \pm 0.03 \quad \frac{R_d}{R_d^{charge}} = 0.97 \pm 0.03 \]

\[ \text{Pb} \quad R_d = 6.57 \pm 0.07 \quad \frac{R_d}{A^{1/3}} = 1.11 \pm 0.01 \quad \frac{R_d}{R_d^{charge}} = 0.98 \pm 0.01 \]

---

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
results for diffraction radii

- DWIA corrections increase strongly with order of minimum
- results for radii agree very well for different minima after DWIA correction
- mass diffraction radii agree within uncertainty with charge radii

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
summary of results

- **results for rms-radii: slightly smaller than charge radii**

<table>
<thead>
<tr>
<th>nucl.</th>
<th>$r_{rms}$[fm]</th>
<th>$r_{rms}^{pc}$[fm]</th>
<th>$r_{rms}/r_{rms}^{pc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>2.28±0.10</td>
<td>2.32</td>
<td>0.98</td>
</tr>
<tr>
<td>Ca</td>
<td>3.22±0.10</td>
<td>3.35</td>
<td>0.96</td>
</tr>
<tr>
<td>Nb</td>
<td>3.96±0.10</td>
<td>4.22</td>
<td>0.94</td>
</tr>
<tr>
<td>Pb</td>
<td>5.20±0.15</td>
<td>5.42</td>
<td>0.96</td>
</tr>
</tbody>
</table>

- **results for diffraction radii: agree within uncertainty with charge radii**

<table>
<thead>
<tr>
<th>nucl.</th>
<th>$R_d^m$[fm]</th>
<th>$R_d^{fit}$[fm]</th>
<th>$\sigma$[fm]</th>
<th>$R_d^c$[fm]</th>
<th>$\sigma_c$[fm]</th>
<th>$R_d^m/R_d^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>2.41±0.09</td>
<td>2.30±0.10</td>
<td>0.46</td>
<td>2.44</td>
<td>0.67</td>
<td>0.99</td>
</tr>
<tr>
<td>Ca</td>
<td>3.78±0.05</td>
<td>3.65±0.30</td>
<td>0.53</td>
<td>3.79±0.04</td>
<td>0.80</td>
<td>1.00</td>
</tr>
<tr>
<td>Nb</td>
<td>5.09±0.05</td>
<td>5.10±0.10</td>
<td>-</td>
<td>5.04±0.04</td>
<td>-</td>
<td>1.01</td>
</tr>
<tr>
<td>Pb</td>
<td>6.66±0.07</td>
<td>6.65±0.05</td>
<td>0.67</td>
<td>6.66±0.04</td>
<td>0.81</td>
<td>1.00</td>
</tr>
</tbody>
</table>

- promising, but not yet precise enough for extraction of neutron radii; analysis of diffraction minima allows better control of systematics than analysis of slope
second generation experiment
C. Tarbert, D. Watts et al., Crystal Ball/TAPS@MAMI

- much better statistics due to 4π-detector (smaller photon energy bins)
- much better control of incoherent background
- covers energy range below 200 MeV where FSI is small (vanishes almost)

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
first preliminary results for neutron skin

- fit of minima with Bessel function
- resolution for first minimum better than $0.005 \text{ fm}^{-1}$
- shift of minima due to FSI corrected with theory

first indication for neutron skin

for final analysis: implement predicted FF’s into pion production model

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
incoherent production - example: 4.4 MeV state in $^{12}\text{C}$

C. Tarbert, D. Watts et al., Crystal Ball/TAPS@MAMI

- incoherent excitations identified by detection of nuclear decay photons: example 4.4 MeV state of $^{12}\text{C}$
- interesting in its own right: access to transition form factors
- in addition:
  knowledge of incoherent components allows cleaner extraction of mass FF’s

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
Conclusions & outlook

Coherent photoproduction of $\pi^0$-mesons is a promising tool for the measurement of nuclear mass form factors

- **advantages:**
  - fairly large cross sections
  - in $\Delta(1232)$ range identical contribution from protons and neutrons

- **analysis:**
  - analysis of diffraction minima allows better control of systematic effects than slope analysis

- **results:**
  - first experiment (published 2005) showed feasibility
  - data from $4\pi$-detector (under analysis) seem to reach sensitivity to extract neutron skin size

- **future:**
  - also light nuclei ($^7$Li under analysis)
  - measurements for isotopic chains
  - other coherent production channels?
coherent production of $\pi^0\eta$-pairs of nuclei

- $\pi^0$ photoproduction so well suited for coherent process because $\Delta(1232)$ excitation non-spin-flip, non-isospin dependent

- $\eta$-photoproduction in $S_{11}(1535)$ range in contrast extremely suppressed in coherent channel since dominantly iso-vector (large cancelation) and spin-flip (impossible on spin-zero nuclei)

- recently discovered: production of $\pi^0\eta$-pairs in threshold region dominated by $D_{33}(1700)$ resonance
  - main reaction mechanism: $\Delta^*(1700) \rightarrow \Delta(1232)\eta \rightarrow N\eta\pi^0$
  - electromagnetic excitation iso-spin independent
  - emission of $\eta$ in s-wave, $\pi^0$ in p-wave
  - no nucleon spin-flip

$\Rightarrow$ well suited for coherent channel
coherent photoproduction of $\pi^0\eta$-pairs: $d(\gamma, \eta\pi^0)d$

- time-of-flight versus energy for deuteron identification

- invariant mass (two-photon) for reaction identification and missing mass (deuteron treated as missing particle) for verification of coherent kinematics

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
\(d(\gamma, \eta\pi^0)d\): total cross section, kinetic energy distributions

**total cross section**

- \(\sigma\) vs \(E_\gamma\) [MeV]

**kinetic energy**

- \(d\sigma/dT_{\text{cm}}\) [nb / MeV] vs \(T_{\text{cm}}\) [MeV]

- \(E_\gamma = 900 - 1100\) MeV
  - \(W = 2628 - 2767\) MeV
  - A. Fix
  - \(\eta\), \(\pi^0\)

- \(E_\gamma = 1100 - 1600\) MeV
  - \(W = 2767 - 3088\) MeV
  - \(\eta\), \(\pi^0\)

- \(E_\gamma = 1600 - 2000\) MeV
  - \(W = 3088 - 3322\) MeV

- \(\eta\) and \(\pi^0\) distributions support dominant \(\Delta^* \rightarrow \Delta(1232)\eta \rightarrow N\eta\pi^0\) contribution:
  - \(T(\pi^0)\) peaks around 100 MeV \((\Delta(1232) \rightarrow N\pi)\)
  - \(T(\eta)\) rises with \(E_\gamma\)

---

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
very preliminary: $^3$He$(\gamma, \eta\pi^0)^3$He

- identification via missing mass
- preliminary total cross section

![Graph showing data and simulations for $E_\gamma=765 - 1400$ MeV](image)

![Graph showing cross section as a function of $E_\gamma$](image)

- qualitative agreement with isotope dependence from Fix's model

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009
Electron Stretcher Accelerator (ELSA)

- Booster synchrotron: 0.5 - 1.6 GeV
- Stretcher ring: 0.5 - 3.5 GeV

Key components:
- Electron gun
- Compton polarimeter
- MALC
- Mott polarimeter
- PETRA cavity
- DORIS cavity
- Bending magnet beamlines for SR experiments
- FZK laboratory

Experiments:
- Medium energy physics experiments
- Linear accelerator (LINAC 1 & 2)
- Medium energy physics
- Booster synchrotron experiments
- DESY cavity
- Electron stretcher accelerator (ELSA)
- Compton polarimeter
- PETRA cavity
- DORIS cavity
- Bending magnet beamlines for SR experiments
- FZK laboratory
Crystal Barrel and TAPS

B. Krusche, PREX 2009 workshop, ECT*, Trento, August 2009