Photoproduction of mesons off light nuclei

- the search for $\eta$-mesic nuclei -

B. Krusche, U. Basel, CBELSA/TAPS, CBALL/TAPS collaborations

Introduction

Experimental setups

- Crystal Barrel & TAPS @ ELSA
- Crystal Ball & TAPS @ MAMI

Experimental results

- coherent photoproduction of $\eta$-mesons: $^3\text{He}(\gamma, \eta)^3\text{He}$, $^7\text{Li}(\gamma, \eta)^7\text{Li}$
- $\pi^0 - p$ back-to-back emission as signal for ‘bound’ $S_{11}$-decays?
- other entrance channels: coherent production of $\eta\pi^0$-pairs?

Conclusions

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Photoproduction of mesons off nuclei - what can we learn?

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

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

- **incoherent**
  \[ \gamma + A \rightarrow \pi^0 + A^* \rightarrow \pi^0 + A + \gamma \]
  - transition form factors
  - Δ in-medium properties
  - spin/iso-spin selection
the story of $\eta$-mesic nuclei

- 1985: Bhalerao & Liu: attractive $\eta$-nucleus interaction for $A \geq 12$
- 1986: Liu & Haider: suggestion of $\eta$-nucleus bound states
- experiments: inconclusive e.g.:
  - Chrien et al. (1988): $\pi^+ + ^{16}O \rightarrow p + ^{15}O + \eta$
  - Johnson et al. (1993): $\pi^+ + ^{18}O \rightarrow \pi^- + ^{18}Ne + \eta$
- 1993 - 2002: analysis of new $\eta$-production data from the proton:
  - larger $\eta N$-scattering lengths
- 1991 - 2002: T. Ueda, C. Wilkin, S.A. Rakityanski and others: suggestions of bound $^2H-$, $^3H-$, $^3He-$, $^4He-$ $\eta$ states

experiments: threshold behavior of $\eta$-production

\[
p + d \rightarrow ^3He + \eta
\]

\[
\gamma + ^3He \rightarrow ^3He + \eta
\]
$\eta$-photoproduction off the proton: resonance contributions?

branching ratios and elm. couplings (PDG):

<table>
<thead>
<tr>
<th>state</th>
<th>$b_\eta$ [%]</th>
<th>$A_{1/2}^p$</th>
<th>$A_{3/2}^p$</th>
<th>$A_{1/2}^n$</th>
<th>$A_{3/2}^n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{13}(1520)$:</td>
<td>0.23±0.04</td>
<td>-24</td>
<td>166</td>
<td>59</td>
<td>139</td>
</tr>
<tr>
<td>$S_{11}(1535)$:</td>
<td>30 - 55</td>
<td>90</td>
<td>-46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{11}(1650)$:</td>
<td>3 - 10</td>
<td>53</td>
<td>-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{15}(1675)$:</td>
<td>0±1</td>
<td>19</td>
<td>15</td>
<td>-43</td>
<td>-58</td>
</tr>
<tr>
<td>$F_{15}(1680)$:</td>
<td>0±1</td>
<td>-15</td>
<td>133</td>
<td>29</td>
<td>-33</td>
</tr>
<tr>
<td>$D_{13}(1700)$:</td>
<td>0±1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{11}(1710)$:</td>
<td>6.2±1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{13}(1720)$:</td>
<td>4±1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $D_{15}(1675)$ has stronger electromagnetic coupling to neutron than to proton
  but parameters quite uncertain:
  $A_{1/2}^n$=-(21-57), $A_{3/2}^n$=-(30-77)
  $b_\eta=0$-1% (PDG), $b_\eta=17$% (ETA-MAID, Chiang et al.)

- interference structure in $S_{11}$-sector?

Data:

- TAPS: B. Krusche et al., PRL74 (1995) 3736
- GRAAL: F. Renard et al., PLB528 (2002) 215
- CLAS: M. Dugger et al., PRL89 (2002) 222002
- Crystal Barrel: V. Crede et al., PRL94 (2005) 012004

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Fermi de-folded proton and neutron data

- **total cross section**
- **cos(\(\Theta_\eta^*\)) < 0**
- **cos(\(\Theta_\eta^*\)) > 0**

- **phenomenological fit of data with:**
  - **proton:** one Breit-Wigner with energy dep. width for \(S_{11}\), one further BW
  - **neutron:** one Breit-Wigner with energy dep. width for \(S_{11}\), two further BW

- **parameters of narrow neutron Breit-Wigner:**
  - **position:** (1668 ± 4) MeV (total), (1670 ± 3) MeV (cos(\(\Theta_\eta^*\)) < 0), (1662 ± 5) MeV (cos(\(\Theta_\eta^*\)) > 0)
  - **width:** (48 ± 15) MeV (total), (26 ± 9) MeV (cos(\(\Theta_\eta^*\)) < 0), (40 ± 20) MeV (cos(\(\Theta_\eta^*\)) > 0)
  - **experimental resolution for width:** \(\approx 25\) MeV

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interaction of mesons in nuclear matter

- 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

- $\pi^0$-mesons: strongly absorbed at energies sufficient to excite $\Delta$; but only very weak interaction at small momenta
  $\rightarrow$ no bound-states possible
- $\eta$-mesons: strong interaction also at very small momenta due to s-wave $S_{11}(1535)$ resonance at threshold
  $\rightarrow$ strong enough for (quasi)-bound states?
coherent $\eta$-photoproduction: search for light $-\eta$-mesic nuclei

- $\eta$-photoproduction dominated by excitation of $S_{11}(1535)$:
  $$\gamma(E1) + N \rightarrow S_{11} \rightarrow N + \eta$$
  $$J_z: \ -1 \quad +1/2 \quad -1/2 \quad -1/2 \quad 0 \quad \rightarrow \text{spin-flip transition}$$

- isospin structure: $A^{IS}_{1/2}/A^P_{1/2} \approx 0.09 \quad \rightarrow \text{dominantly isovector}$

- expectation for light nuclei:
  1) $^4\text{He}$: $J=0$, $I=0$, isoscalar, non spin-flip \quad \rightarrow \text{very small signal}
     (not seen, only upper bounds, V. Hejny et al.)
  2) $^2\text{H}$: $J=1$, $I=0$, isoscalar, spin-flip \quad \rightarrow \text{small signal}
     (seen, almost in agreement with expectations)
  3) $^3\text{He}$: $J=1/2$, $I=1/2$, isovector, spin-flip \quad \rightarrow \text{‘large’ signal}

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Electron Stretcher Accelerator (ELSA)

- Booster synchrotron
  - 0.5 - 1.6 GeV
- Stretcher ring
  - 0.5 - 3.5 GeV
- Bending magnet beamlines for SR experiments
- Medium energy physics experiments

- detector tests
- skew quadrupoles
- injection septa
- extraction septa
- superconducting solenoid
- DORIS cavity
- PETRA cavity
- tune jump quadrupole

- linac 2 (26 MeV)
- linac 1 (20 MeV)
- linac 1 (50 keV)
- electron gun
- Mott polarimeter
- Compton polarimeter
- Møller polarimeter
- crystal barrel

- electron stretcher accelerator (ELSA)
- DESY cavity
- DORIS cavity
- PETRA cavity
- tune jump quadrupole
- extraction septa
- superconducting solenoid
- GDH

- FZK laboratory
- BN0
- BN1
- BN2
- BN3
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 0.4ns
- linear accelerator structures
- constant B field ⇒ varying radii (18, 51, 90 return cycles)
- very efficient acceleration and continuous mode
- high current (0.1mA)

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

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Experiments: Crystal Ball & Crystal Barrel with TAPS

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

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

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TAPS Crystal Ball - at MAMI

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\( \eta \)-photoproduction from \(^3\)He - threshold behavior

M. Pfeiffer et al., PRL 92 (2005) 252001

- evidence for strong final state interaction of the \( \eta \)-meson

- threshold enhancement of coherent part

- isotropic angular distribution of coherent part at threshold

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new $^3$He experiment - improved statistics

reaction identification:
- invariant mass analyses for $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$
- missing energy analysis for coherent kinematics:

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new $^3$He experiment - coherent $\eta$-production

- very steep rise of total cross section at threshold confirmed;
- similar to hadron induced reaction: $pd \rightarrow ^3$He$\eta$ (T. Mersmann et al., PRL 98 (2007) 242301)

- phase space reduced amplitudes:

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differential cross section

- $\eta \rightarrow 2\gamma$

- $\eta \rightarrow 6\gamma$

- black lines: angular dependence of $^3$He form factor

threshold angular distributions do not behave as expected from form factor dependence:

$$\frac{d\sigma}{d\Omega} = a + b \cdot \cos(\Theta) + c \cdot \cos^2(\Theta)$$

$$\alpha = \frac{b}{a}$$

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coherent $\eta$-photoproduction off $^7$Li

- $\eta \rightarrow 2\gamma$
- $\eta \rightarrow 6\gamma$

Total cross section for coherent channel:
search for $\eta$-mesic nuclei

- G. Sokol et al., search in: $\gamma + ^{12}C \rightarrow N + \eta (A - 1) \rightarrow N + \pi^+ + n + (A - 2)$
- similar principle for photoproduction from $^3$He:

- excess of $\pi^0$-p back-to-back emission at the $\eta$-threshold (3.5$\sigma$)

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new $^3\text{He}$ experiment: $\pi^O-p$ back-to-back pairs

$\pi^O-p$ back-to-back pairs:
- peak structure at coherent threshold is statistically significant...

Simulation of opening angle behavior for quasi-free $\pi^O$ production and $\eta$-mesic state

But: behavior of background from single $\pi^O$ production via nucleon resonances highly non-trivial →

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Dependence of $\pi^0 - p$ excitation functions on opening angle

- excitation functions - arbitrarily scaled
- excitation functions $\times E_\gamma^6$

- nucleon resonances produce opening angle dependent structures in excitation functions
- subtraction of excitation functions for different opening angles can produce artificial structures almost everywhere
- basically no hope to isolate tiny structure from $\gamma$-mesic state in this complicated landscape!

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summary: coherent $\eta$-photoproduction off light nuclei

- strong threshold enhancement for $\gamma^3\text{He} \to ^3\text{He} \eta$ confirmed
- angular distributions close to threshold different from form factor expectation
- structure in $\pi^0 - p$ pairs obscured by background from resonance contributions to quasi-free $\pi^0$ production
- first preliminary results also for $\gamma^7\text{Li} \to ^7\text{Li} \eta$
- cross section for $\gamma^7\text{Li} \to ^7\text{Li} \eta$ smaller by roughly one order of magnitude (corresponds to ratio of form factors)
- threshold enhancement for $\gamma^7\text{Li} \to ^7\text{Li} \eta$ less pronounced
- comparison: $\gamma^3\text{He} \to ^3\text{He} \eta$ and $\gamma^7\text{Li} \to ^7\text{Li} \eta$

what about $^4\text{He}$?

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MAMI
**what about $\eta$-mesic $^4$He?**

- $\eta$-photoproduction dominated by excitation of $S_{11}(1535)$:
  \[
  \gamma(E1) + N \rightarrow S_{11} \rightarrow N + \eta
  \]
  \[J_z: \quad -1 \quad +1/2 \quad -1/2 \quad -1/2 \quad 0 \quad \Rightarrow \text{spin-flip transition}\]

- Isospin structure: $A^{I_1S_1}/A^p \approx 0.09$ \(\Rightarrow\) dominantly isovector

- \(\Rightarrow\) coherent $\eta$-photoproduction ruled out for $I=J=0$ nuclei

- **possible way out:** coherent photoproduction of $\eta\pi^O$-pairs

  - Dominant process close to threshold:
    \[
    \gamma p \rightarrow D_{33}(1700) \rightarrow \eta P_{33}(1232) \rightarrow \eta\pi^O p
    \]
  - V. Kashevarov et al., EPJA (2009)

  - $\Rightarrow$ no spin-flip,
    identical amplitude for $p$, n
  - $\Rightarrow$ ideal entrance 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
$d(\gamma, \eta\pi^0)d$: total cross section, kinetic energy distributions

- **total cross section**

  - $E_\gamma$ [MeV]: 1000 1500 2000 2500
  - $\sigma$ [µb]: 0 0.05 0.1 0.15

- **kinetic energy**

  - $E_\gamma = 900 - 1100$ MeV, $W = 2628 - 2767$ MeV
  - $E_\gamma = 1100 - 1600$ MeV, $W = 2767 - 3088$ MeV
  - $E_\gamma = 1600 - 2000$ MeV, $W = 3088 - 3322$ MeV

- **total cross section in reasonable agreement with predictions**

- **$T$ 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 $E_\gamma$

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very preliminary: $^3\text{He}(\gamma, \eta\pi^0)^3\text{He}$

- identification via missing mass
- preliminary total cross section

- qualitative agreement with isotope dependence from Fix' model

proposal to measure $\gamma + ^4\text{He} \rightarrow ^4\text{He} + \pi^0\eta$ accepted for MAMI

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Conclusions

coherent photoproduction of $\eta$-mesons:
- strong threshold enhancement for $\gamma + ^3\text{He} \rightarrow \eta + ^3\text{He}$
  similar like in hadron induced reactions $\rightarrow$ final state property
- fast variation of shape of angular distributions at threshold
- coherent $\eta$-photoproduction off $^7\text{Li}$ identified for the first time, magnitude smaller by one order of magnitude, threshold enhancement less pronounced

$\pi^O - p$ back-to-back pairs:
- possible signal obscured by background from quasi-free single $\pi^O$-production through nucleon resonances

other channels:
- detailed study of coherent photoproduction of $\pi^O\eta$-pairs under way

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