Search for mesic nuclei in the photoproduction of \( \eta \) and \( \eta' \) mesons off light nuclei

I. Keshelashvili

Group of Prof. B. Krusche
University of Basel
Outline

✔ Introduction
✔ Experimental Setup
✔ Data Analysis
✔ Results
✔ Conclusion
Low Noise/Low Power (LNP) preamplifier for APD and VPTT

W. Erni, M. Steinacher, I. Keshelashvili, B. Krusche

Material: PbW$_4$ - 22 $X_0$

Crystal size: 2 cm x 2 cm x 20 cm

Energy resolution: 1.54% / $\sqrt{E}$/GeV+0.3%

Number of crystals: 15552

Forward EMC: 3600 – Basel LNP

Per crystal 2xAPD or VPTT

Cooled down to -25 °C
Basel group EMC @ PANDA, PreAmp & HV

2013

Development

Test setup

Mass-production

2014

Apache/PHP/MySQL

ROOT based DAQ + slow control

LINUX

RS232

FPGA Generator

RS232

NIM - HV
ISEG

<10nA

1xCH

Pulser

Trigger

2xCH

RS232

Power
Low V / I[nA]

1xCH

USB3

VME - SADC
Struck
12bit, 500MS/s

2xCH

'APD'

LNP PreAmp
Introduction
**Strong Interaction**

![Graph showing coupling constant αq(E) vs energy in GeV](image)

<table>
<thead>
<tr>
<th>Hadron</th>
<th>cτ</th>
<th>Mass (GeV)</th>
<th>Flavor Content</th>
<th>Detection Channel</th>
</tr>
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<tbody>
<tr>
<td>π^0</td>
<td>25 nm</td>
<td>0.13</td>
<td>uudd</td>
<td>γγ</td>
</tr>
<tr>
<td>π^+</td>
<td>7.8 m</td>
<td>0.14</td>
<td>ud</td>
<td>direct</td>
</tr>
<tr>
<td>π^-</td>
<td>7.8 m</td>
<td>0.14</td>
<td>dū</td>
<td>direct</td>
</tr>
<tr>
<td>η</td>
<td>0.17 nm</td>
<td>0.55</td>
<td>uuddss</td>
<td>γγ</td>
</tr>
<tr>
<td>ω</td>
<td>23 fm</td>
<td>0.78</td>
<td>uuddss</td>
<td>π^+π^-π^0</td>
</tr>
<tr>
<td>η'</td>
<td>0.98 pm</td>
<td>0.96</td>
<td>uuddss</td>
<td>π^+π^-η</td>
</tr>
<tr>
<td>K^+</td>
<td>3.7 m</td>
<td>0.49</td>
<td>uś</td>
<td>direct</td>
</tr>
<tr>
<td>K^-</td>
<td>3.7 m</td>
<td>0.49</td>
<td>ūs</td>
<td>direct</td>
</tr>
<tr>
<td>K^0</td>
<td>27 mm</td>
<td>0.50</td>
<td>dś</td>
<td>π^+π^-</td>
</tr>
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</table>
Why coherent production?

1) Coherent

\[ \gamma \rightarrow p \eta \n\]

2) Break-Up (main BG)

\[ \gamma \rightarrow p p \eta \n\]

3) Incoherent (XS small)

\[ \gamma \rightarrow p n n n \eta \n\]

4) Double meson

\[ \gamma \rightarrow p n \pi^0 \eta \n\]
History

1985: Bhalerao & Liu: coupled-channel analysis attractive s-wave $\eta$-A; $\pi$-induced for $A \geq 12$
scatt. lengths: Re: 0.27-0.28 fm Im: 0.19-0.22 fm;

1986: Liu & Haider:
suggestion of $\eta$-nucleus bound states for $A > 10$

experiments: inconclusive evidence:
Chrien et al. (1988): $\pi^+ + ^{16}\text{O} \rightarrow p + ^{15}\text{O}$
Johnson et al. (1993): $\pi^+ + ^{18}\text{O} \rightarrow \pi^- + ^{18}\text{Ne}$
Sokol et al. (99): $\gamma + ^{12}\text{C} \rightarrow p(n) + ^{11}\text{B(C)} \rightarrow \pi^+ + n + X$

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 $^2\text{H}$-, $^3\text{H}$-, $^3\text{He}$-, $^4\text{He}$-$\eta$ states
Why is the $\eta$-meson case special?

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

- Expectation for light nuclei:

  I) $^4$He: $J=0$, $I=0$, isoscalar, non spin-flip
     \(\rightarrow\) very small signal
     (not seen, only upper bounds, V. Hejny et al.)

  II) $^2$H: $J=1$, $I=0$, isoscalar, spin-flip
     \(\rightarrow\) small signal
     (seen, almost in agreement with expectations)

  III) $^3$He: $J=1/2$, $I=1/2$, isovector, spin-flip
     \(\rightarrow\) ‘large’ signal
Photoproduction of eta-mesic $^3$He
ANKE - Excitation function: $dp \rightarrow ^3\text{He}\eta$

$\chi^2/\text{n}_{\text{free}} = 0.82$

$\eta$ momentum $p_\eta$ [MeV/c]

ANKE @ COSY, PRL 98, 242301
Experiment
MAMI (Mainzer Mikrotron)
How to get the photon energy?

$$E_\gamma = E_e - E_e'$$
Crystal Ball / TAPS Detector

Polarized Target

Crystal Ball
672 NaI(Tl)

PID 24 Pl.Sci.

TAPS
BaF$_2$ + PWO

VETO 384 Pl.Sci.
Crystal Ball detector at SPEAR @ SLAC

- SPEAR began 1972
- $e^- e^+ @ 3\text{GeV}$
- $J/\psi$ meson
  Nobel price 1976
- +many charmonium states
- SLAC, DASY, BNL, MAMI
Crystal Ball / TAPS Detector

Invariant Mass
Missing Energy or Mass
Pulse Shape
TOF – Time-Of-Flight
Analysis
Data Analysis

TAPS - Tagger

TAPS Time

PID Scintillators

\[ M_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos \phi_{12})} \]

\[ M_p = 134.8 \text{ MeV} \]

\[ M_p = 547.3 \text{ MeV} \times 30 \]

\[ \frac{d\sigma}{d\Omega}(E_{\gamma}, \theta) = \frac{N_{\text{event}}(E_{\gamma}, \theta)}{\epsilon(E_{\gamma}, \theta) \cdot \Gamma_{\text{BR}} \cdot N_{\text{target}} \cdot N_{\text{scaler}}(E_{\gamma}) \cdot \epsilon(E_{\gamma}) \cdot \Omega} \]
Results

$\gamma + ^3\text{He} \rightarrow ^3\text{He} + \eta$
Coherent photoproduction of $\eta$-mesons off $^3$He – search for $\eta$-mesic nuclei

Coherent $\eta$ photoproduction off $^3\text{He}$

ME coherent $\eta$ off $^3\text{He}$ - $2\gamma$ (left) and $3\pi^0/6\gamma$ (right)
Coherent $\eta$ photoproduction off $^3$He

Shevchenko et al. 3N system in a microscopic few-body description. Strong dependence on the elastic $\eta N$ rescattering. Strong threshold effects, bad reproduction above the breakup threshold

Fix et al. $^3$He and $^3$H in PWIA, in a distorted-wave impulse approximation (DWIA) using optical potential. Strong FSI effects. Underestimates XS.

Tiator et al. model was based on the PWIA. Strongly underestimates measured XS and does not reproduce the energy dependence.
Coherent $\eta$ photoproduction off $^3\text{He}$

(Red) $\eta \rightarrow 2\gamma$ decay (Blue) $\eta \rightarrow 6\gamma$ decay

The behavior of the angular distributions of the PWIA is dominated by the nuclear form factor, which is responsible for the strong forward peaking.

Solid (dashed) curves: PWIA with realistic (isotropic) angular distribution for $\gamma n \rightarrow n\eta$
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 $\eta$-mesic state in this complicated landscape!
Photoproduction of $\eta$ – mesic $^3\text{He}$

$\gamma + ^3\text{He} \rightarrow (\eta ^3\text{He}) \rightarrow p + \pi^0 + X$

Excitation functions

Excitation functions $\times E_\gamma^6$
Summary I

\[ \gamma + ^3\text{He} \rightarrow ^3\text{He} + \eta \]

✗ Strong threshold enhancement and shape of angular distributions confirmed

✗ Evidence for very strong FSI effects

✗ Alternative decay channel \( \pi^0\)-p back-to-back suffers from complicated background structure, signal not confirmed
Coherent $\eta$ -photoproduction off $^7$Li nuclei

(Ph.D. work of Yasser Maghrbi)
Coherent η- photoproduction off $^7$Li

ME coherent η off $^7$Li - $2\gamma$ (left) and $3\pi^0/6\gamma$ (right)
Coherent $\eta$- photoproduction off $^7$Li

- $\eta \rightarrow 2\gamma$
- $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$

\[ \sigma [\mu b / A] \]

$E_\gamma$ [MeV]
Coherent $\eta$- photoproduction off $^7$Li

![Graph showing $\sigma$ (in $\mu$b/A) versus $E_\gamma$ (in MeV) for $^7$Li and $^3$He coherently produced $\eta$ mesons.]
Photoproduction of $\eta$ – mesic $^7\text{Li}$

$$\gamma + ^7\text{Li} \rightarrow (\eta^7\text{Li}) \rightarrow p + \pi^0 + X$$
Coherent $\eta'$ -photoproduction off LD and $^3$He nuclei
(Ph.D. work of Roman Trojer)
Coherent $\eta'$- photoproduction off LD

$$\gamma + d \rightarrow X + \eta' \rightarrow X + \eta(\gamma\gamma)\pi^0(\gamma\gamma)\pi^0(\gamma\gamma)$$
Coherent $\eta'$- photoproduction off LD

\[ \gamma + d \rightarrow X + \eta' \rightarrow X + \eta(\gamma\gamma)\pi^0(\gamma\gamma)\pi^0(\gamma\gamma) \]

\[ \sigma [\mu b] \quad E_\gamma [\text{MeV}] \]

Graph showing the cross-section $\sigma$ as a function of $E_\gamma$.
Coherent $\eta'$- photoproduction off $^3$He

$$\gamma + ^3\text{He} \rightarrow X + \eta' \rightarrow X + \eta(\gamma\gamma)\pi^0(\gamma\gamma)\pi^0(\gamma\gamma)$$
Coherent $\eta'$- photoproduction off $^3\text{He}$

$\gamma + ^3\text{He} \rightarrow X + \eta' \rightarrow X + \eta(\gamma\gamma)\pi^0(\gamma\gamma)\pi^0(\gamma\gamma)$
\( \times \) Similarities between \(^3\)He and \(^7\)Li cross section shows strong threshold enhancement

\( \times \) \(^7\)Li decay channel \(\pi^0\)-p back-to-back suffers from complicated background structure, signal not confirmed

\( \times \) \(\eta'\) show also very rapid rise of the total cross section
We have accepted proposal by the PAC

A2-16/09  Coherent production of $\pi^0\eta$ pairs off $^4He$

Spokespersons  I.Jaegle, I.Keshelashvili, B.Krusche (Basel)
Beam  1558MeV, circularly polarized
Target  liquid $^4He$
Beam Time  700h
$\eta\pi^0$ - photoproduction off deuteron
\( \eta \pi^0 \)- photoproduction off deuteron

Preliminary results: Ph.D. Work of A. Käser
Thank you for your Attention

University of Basel

Group of Prof. Bernd Krusche

Group members

Manuel Dieterle | Stefanie Garni | Alexander Käser
Irakli Keshelashvili | Markus Oberle | Tigran Rostomyan | Thomas Strub
Dominik Werthmüller | Lilian Witthauer
allows to investigate sequential decays
- $\eta$ works as isospin filter: Due to isospin conservation, only higher energetic $N^*(\Delta^*)$ resonances can decay into a $\eta N^*(\Delta^*)$ intermediate state

$\eta\pi^0$ - photoproduction off deuteron

$\eta\pi$ - photoproduction off deuteron

Notation:
$L_{2I2J} ; L=0(S), 1(P), 2(D),...$
$\eta\pi^0$- photoproduction off deuteron

![Graph showing photoproduction data at different energies.](image)

- $W = 1665$ MeV
- 1695 MeV
- 1725 MeV
- 1755 MeV
- 1785 MeV
- 1815 MeV

$\frac{d\sigma}{dm}$ [\(\mu b/MeV\)]