Search for η-mesic helium with the WASA-at-COSY facility

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Symposium: "Fundamental physics with exotic atoms and radiation detectors"

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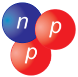
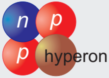
Outline

Classical and "exotic" bound systems

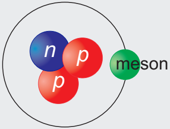


Classical nucleus
bound system of nucleons (p, n)

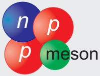
"Exotic" systems



Hypernucleus
bound system of nucleons (p, n)
and hyperon (Λ, Σ)

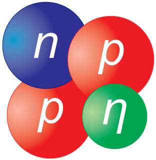


Mesic atom
charged meson (π^-, K^-)
orbiting around a nucleus



Mesic nucleus
bound system of nucleons (p, n)
and neutral meson (η, η', ω, ...)

Mesic helium
^{3}He-η



The bound state of a helium nucleus ($^{3}_{2}$He) with a neutral η meson as a result of the **strong interaction**

$$m_{(^{3}\text{He-}\eta)_{bound}} = m_{\eta} + m_{^{3}\text{He}} - B_s$$

Meson η
$(u\bar{u},\ d\bar{d},\ s\bar{s})$

$$m_{\eta} = 547.862\ MeV$$
$$\Gamma = 1.31\ keV$$
$$I^{G}(J^{PC}) = 0^{+}(0^{-+})$$
$$\tau = 5.02 \cdot 10^{-19}\ s$$

(PDG 2020): P. A. Zyla *et al. Prog. Theor. Exp. Phys.* **8** (2020), 083C01

Theoretical predictions

The interaction between the η meson and a nucleon
is attractive and strong

R. Bhalerao, L. C. Liu, *Phys. Lett. B* **54** (1985), 685

$\Downarrow$

The possibility of the existence of η-mesic bound states
was postulated for atomic nuclei with $A \geqslant 12$

Q. Haider, L. C. Liu, *Phys. Lett. B* **172** (1986), 257; *Phys. Rev. C* **34** (1986), 1845

Recent theoretical studies of hadronic- and photoproduction
of η meson support the existence of light mesic nuclei, like
$(^3\text{He-}\eta)_{bound}$

S. Wycech *et al. Phys. Rev. C* **52** (1995), 544.

N. G. Kelkar *et al. Rep. Prog. Phys.* **76** (2013), 066301

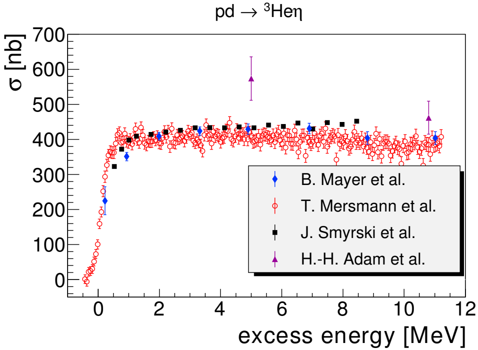
A. Fix, O. Kolesnikov. *Phys. Rev. C* **97** (2018), 044001

N. Barnea *et al. Phys. Lett. B* **771** (2017), 297: $a_{\eta N} \sim 1\ fm$

J.-J. Xie *et al. Phys. Rev. C* **95** (2017), 015202: $B_s \sim 0.3\ MeV$, $\Gamma \sim 3\ MeV$

Experimental indications of the existence of the $(^3\text{He-}\eta)_{bound}$

Total cross section σ of the $dp(pd) \rightarrow {}^3\text{He}\eta$ reactions as a function of excess energy $Q_{^3\text{He}\eta}$



B. Mayer *et al. Phys. Rev. C* **53** (1996), 2068

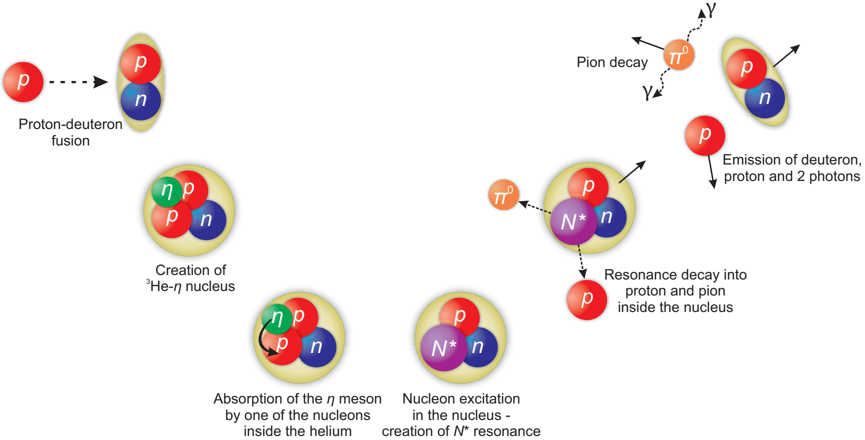
T. Mersmann *et al. Phys. Rev. Lett.* **98** (2007), 242301

J. Smyrski *et al. Phys. Lett. B* **649** (2007), 258

H.-H. Adam *et al. Phys. Rev. C* **75** (2007), 014004

The sharp increase in the total cross-section σ for the $dp(pd) \rightarrow {}^3\text{He}\eta$ reactions close to the threshold indicates the existence of a strong interaction between the η and the helium nucleus.

Kinematical mechanism of the $pd \longrightarrow (^3\text{He-}\eta)_{bound} \longrightarrow dp\pi^0$ reaction



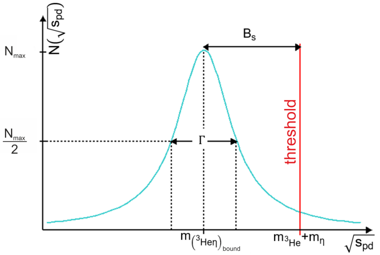
Monte Carlo simulation – theoretical assumptions

Breit-Wigner distribution

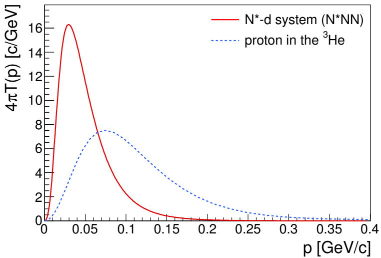
Spectator model

$$N(\sqrt{s_{pd}}) = \frac{\Gamma^2/4}{\left(\sqrt{s_{pd}} - (m_\eta + m_{3He} - B_s)\right)^2 + \Gamma^2/4}$$

$$|\mathbb{P}_d|^2 = m_d^2$$



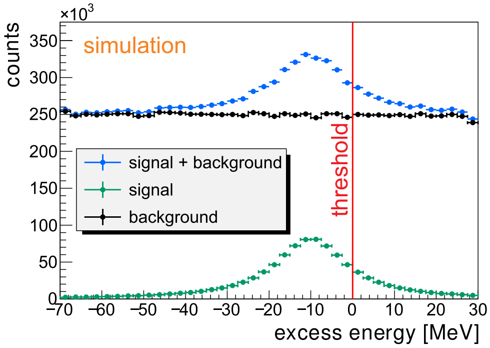
The bound state has a resonant structure with a binding energy B_s and a width Γ



The momentum distribution of the N* resonance in the system N*-deuteron

N. G. Kelkar, H. Kamada, M. Skurzok. *Int. Jour. Mod. Phys. E* **28** (2019), 1950066
N. G. Kelkar, M. Skurzok *et al. Nucl. Phys. A* **996** (2020), 121698

Experimental method



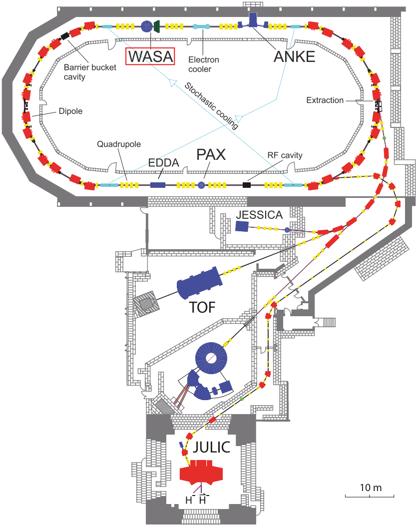
$$pd \to ({}^3\text{He-}\eta)_{bound} \to d\pi^0$$
$$+$$
$$pd \to d\pi^0$$

$$pd \to d\pi^0$$

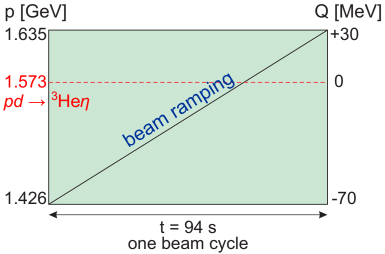
$$pd \to ({}^3\text{He-}\eta)_{bound} \to d\pi^0$$

The existence of the $({}^3\text{He-}\eta)_{bound}$ should manifest as a resonance-like structure below the η meson production threshold

Synchrotron COSY
(**Co**oler **Sy**nchrotron)



P. Moskal, W. Krzemień, M. Skurzok, *COSY proposal No. 186.3*, 2014



Proton beam momentum: from 1.426 $\frac{GeV}{c}$ to 1.635 $\frac{GeV}{c}$

Target: frozen deuterium droplets (pellets)

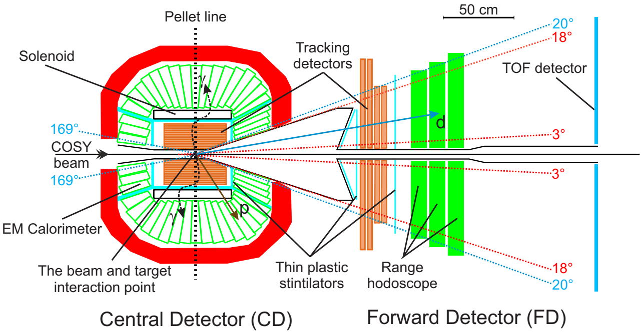
Cycle time: 94 s

Effective time of measurement: 245 hours

The largest sample of data for the search for meson nuclei has been collected

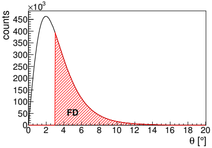
Reaction products registration

The WASA (**W**ide **A**ngle **S**hower **A**pparatus) detection system

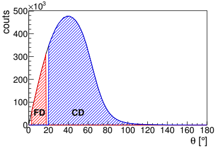


Products of the $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow d\pi^0\ [\pi^0 \rightarrow \gamma\gamma]$ reaction:

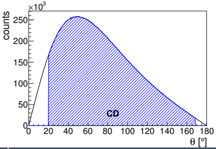
deuterons



protons

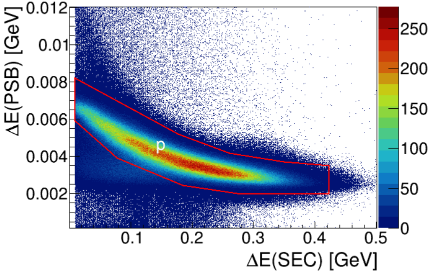


photons

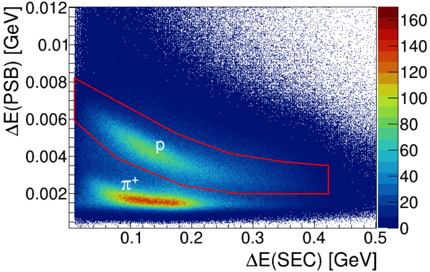


Protons

Simulation:
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$



Experimental data

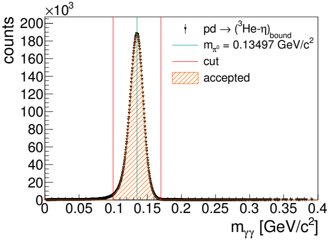


Spectrum of the energy loss in the Plastic Scintillator Barrel ΔE(PSB) shown as a function of the energy deposited in the Electromagnetic Calorimeter ΔE(SEC)

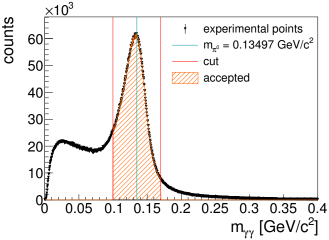
Particle identification – cont.

Neutral pions

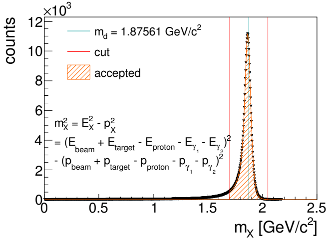
Simulation:
$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$

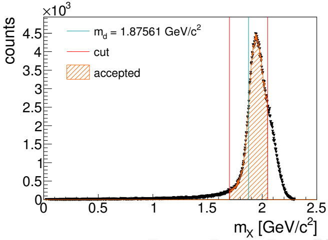


Experimental data



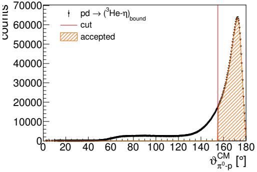
Deuterons



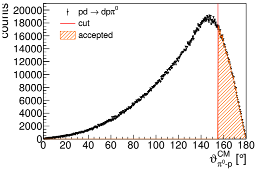


Relative angle between the pion and the proton in the CM system

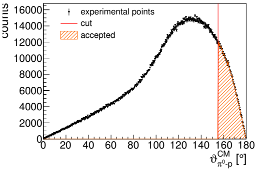
Simulation (signal): $pd \rightarrow ({}^{3}\text{He-}\eta)_{bound} \rightarrow d\pi^0$



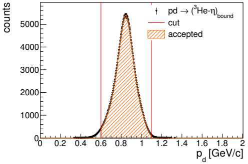
Simulation (background): $pd \rightarrow d\pi^0$

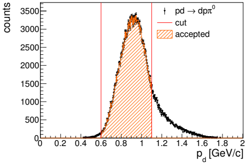


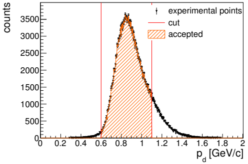
Experimental data



Deuteron momentum

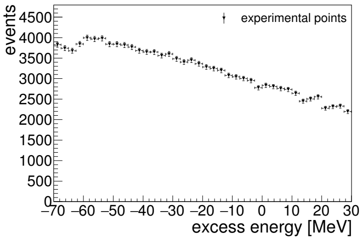






Excitation function for the $pd \to dp\pi^0$ reaction

Number of counts

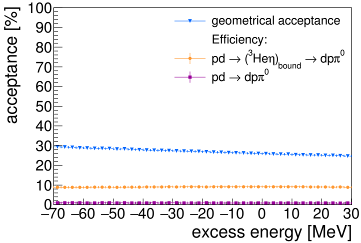


Total cross section:

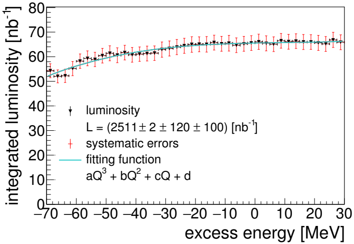
$$\sigma(Q) = \frac{N(Q)}{\varepsilon(Q) \cdot L(Q)}$$

N – number of experimental events;
ε – full detection efficiency;
L – integrated luminosity

Efficiency



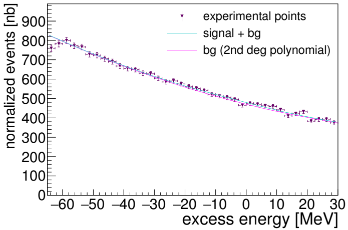
Luminosity



Determination of the upper limit of the cross section for the $pd \to (^3\text{He-}\eta)_{bound} \to dp\pi^0$ process

Excitation function does not reveal narrow resonance structure

$\Uparrow$



$$\frac{A \cdot \frac{\Gamma^2}{4}}{(Q-B_s)^2+\frac{\Gamma^2}{4}} + BQ^2 + CQ + D$$

Breit-Wigner (signal) + pol2 (background)

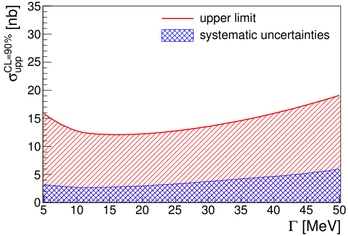
B_s, Γ – fixed parameters;
A, B, C, D – free parameters

$$\Rightarrow \quad \sigma_{upp}^{CL=90\%} = k \cdot \sigma_A$$

($k = 1.64485$ (for CL $= 90\%$) [PDG])

dla $pd \to (^3\text{He-}\eta)_{bound} \to dp\pi^0$

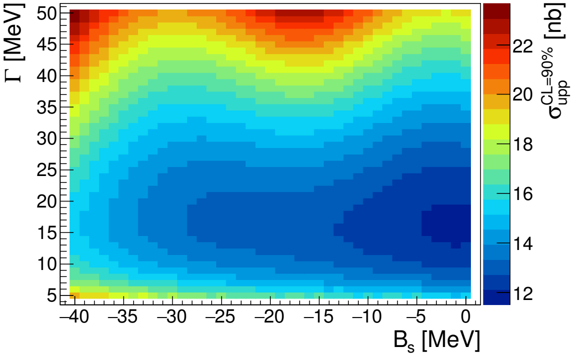
$\Downarrow$



Result

$$\sigma_{pd \to (^3\text{He-}\eta)_{bound} \to dp\pi^0} < 24 \ nb$$

Upper limit of the total cross section for the $pd \to (^3\text{He-}\eta)_{bound} \to dp\pi^0$ process



The final results of the analysis of the data collected in this experiment were approved by the WASA-at-COSY collaboration and published:
P. Adlarson, . . . , A. Khreptak *et al.* (WASA-at-COSY Collaboration). *Phys. Rev. C* **102** (2020), 044322

Summary and Conclusions

- The exclusive measurement of the $pd \rightarrow dp\pi^0$ reaction was performed with the WASA-at-COSY facility using the ramped beam technique.
- The analysis of the experimental data was carried out.
- The obtained excitation function for the $pd \rightarrow dp\pi^0$ process does not reveal the resonance-like structure which could be interpreted as the indication of the ^{3}He-η bound state.
- **Result:** the upper limit of the total cross section was for the first time determined for the $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$ reaction ($\sigma_{upp}^{CL=90\%} \in (13, 24)\ nb$).

Thank you for your attention

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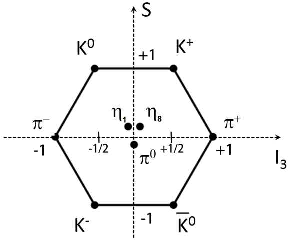
Motivation

- Search for a new kind of nuclear matter
- Investigation of an η meson interaction with nucleons inside a nuclear matter
  N. G. Kelkar *et al. Rept. Progr. Phys.* **76** (2013), 066301;
  H. Machner. *J. Phys. G* **42** (2015), 043001
- Study of the quark structure of the η meson
  (Contribution of the flavour singlet component ($|\eta_0\rangle$) of the quark-gluon wave function of the η; the binding energy is sensitive to $|\eta_0\rangle$)
  S. D. Bass, A. W. Thomas. *Phys. Lett. B* **634** (2006), 368;
  S. D. Bass. *Acta Phys. Pol. B Proc. Suppl.* **2** (2009), 11;
  S. D. Bass, A. W. Thomas. *Acta Phys. Pol. B* **41** (2010), 2239
- Study of $N^*(1535)$ resonance properties in nuclear matter
  – chiral doublet model
  D. Jido *et al. Phys. Rev. C* **66** (2002), 045202;
  D. Jido *et al. Nucl. Phys. A* **721** (2003), C665
  – chiral unitary model
  T. Inoue, E. Oset. *Nucl. Phys. A* **710** (2002), 354;
  H. Nagahiro *et al. Phys. Rev. C* **68** (2002), 035205

η meson

mass	547.862 ± 0.017 *MeV*
width	1.31 ± 0.05 *keV*
$I^G(J^{PC})$	$0^+(0^{-+})$
Decay mode	**Branching ratio**
$\eta \to 2\gamma$	$39.41 \pm 0.20\%$
$\eta \to 3\pi^0$	$32.68 \pm 0.23\%$
$\eta \to \pi^+\pi^-\pi^0$	$22.92 \pm 0.28\%$
$\eta \to \pi^+\pi^-\gamma$	$4.22 \pm 0.08\%$
others	0.77%

Spin, isospin, charge, strangeness $= 0$



$$|\eta_0\rangle = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$
$$|\eta_8\rangle = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

The observed η meson is a quantum superposition of η_0 and η_8 states:

$$|\eta\rangle = \cos\theta\,|\eta_8\rangle - \sin\theta\,|\eta_0\rangle,$$

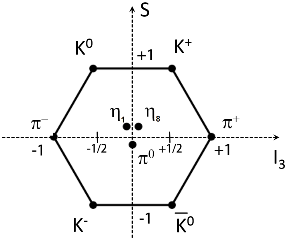
where θ – mixing angle ($\theta = -15.5^\circ \pm 1.3^\circ$)

P. A. Zyla *et al.* (Particle Data Group), *Prog. Theor. Exp. Phys.* **8** (2020), 083C01;
A. Bramon *et al.* *Eur. Phys. J. C* **7** (1999), 271

η' meson

mass	957.78 ± 0.06 *MeV*
width	0.188 ± 0.006 *MeV*
$I^G(J^{PC})$	$0^+(0^{-+})$
Decay mode	**Branching ratio**
$\eta' \to \pi^+\pi^-\eta$	$42.5 \pm 0.5\%$
$\eta' \to \rho^0\gamma$	$29.5 \pm 0.4\%$
$\eta' \to \pi^0\pi^0\eta$	$22.4 \pm 0.5\%$
$\eta' \to \omega\gamma$	$2.52 \pm 0.07\%$
$\eta' \to 2\gamma$	$2.307 \pm 0.033\%$
others	0.77%

Spin, isospin, charge, strangeness $= 0$



$$|\eta_0\rangle = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$
$$|\eta_8\rangle = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

The observed η' meson is a quantum superposition of η_0 and η_8 states:

$$|\eta'\rangle = \sin\theta\,|\eta_8\rangle + \cos\theta\,|\eta_0\rangle,$$

where θ – mixing angle ($\theta = -15.5^\circ \pm 1.3^\circ$)

P. A. Zyla *et al.* (Particle Data Group), *Prog. Theor. Exp. Phys.* **8** (2020), 083C01;
A. Bramon *et al.* *Eur. Phys. J. C* **7** (1999), 271

Scattering theory

At the low momenta the scattering matrix:

$$S = \frac{a}{1 - ipa},$$

p – a complex relative η-He momentum at some distance below the threshold;
a – a scattering length.

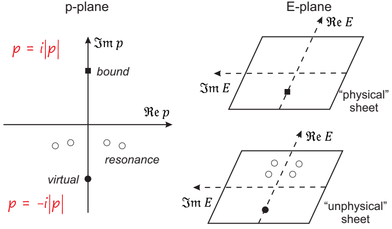
$$E = \frac{p^2}{2\mu}$$

$$\Re\mathfrak{e}\ E = \frac{(\Re\mathfrak{e}\ p)^2 - (\Im\mathfrak{m}\ p)^2}{2\mu}; \Im\mathfrak{m}\ E = \frac{(\Re\mathfrak{e}\ p)(\Im\mathfrak{m}\ p)}{\mu}$$

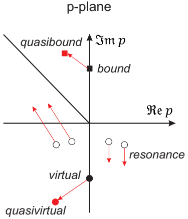
When interaction is described only by a real potential ($\Im\mathfrak{m}\ a = 0$):
($\Im\mathfrak{m}\ p > 0$) i ($\Re\mathfrak{e}\ E < 0$) $\Rightarrow$ bound state;
($\Im\mathfrak{m}\ p < 0$) i ($\Re\mathfrak{e}\ E < 0$) $\Rightarrow$ virtual state

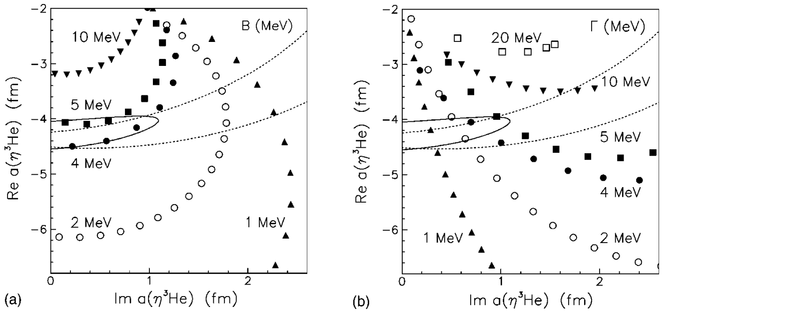
In case of inelastic interaction (the interaction potential includes the imaginary part $\Im\mathfrak{m}\ a \neq 0$) – the positions of the poles of the matrix S shift

$\Im\mathfrak{m}\ a = 0$



$\Im\mathfrak{m}\ a \neq 0$





Binding energy B of the η-^{3}He (a) and width Γ (b) as a function of the imaginary and real parts of the η-^{3}He scattering length. The results for different values of B and Γ.
A. Sibirtsev *et al.* *Phys. Rev. C* **70** (2004), 047001

Bound state:

$$|\mathfrak{Im}\ a_{\eta\text{-}^3\mathrm{He}}| < |\mathfrak{Re}\ a_{\eta\text{-}^3\mathrm{He}}|; \qquad \mathfrak{Im}\ a_{\eta\text{-}^3\mathrm{He}} > 0; \qquad \mathfrak{Re}\ a_{\eta\text{-}^3\mathrm{He}} < 0 \text{ (attraction)}$$

Q. Haider, L. C. Liu. *Phys. Rev. C* **66** (2002), 045208;
H. Machner. *Acta Phys. Pol. B* **45** (2014), 705

Search for heavy η-mesic nuclei

BNL (Brookhaven National Lab): $\pi^+ + A \rightarrow p + (A-1)_\eta$; targets ($A$): Li, C, O, Al
R. E. Chrien *et al. Phys. Rev. Lett.* **60** (1988), 2595

LAMPF (Los Alamos Meson Physics Facility): search for the mesic ^{18}F-η nucleus in the $\pi^+ + {}^{18}\text{O} \rightarrow \pi^- + {}^{18}\text{Ne}$ reaction (DCX).
J. D. Johnson *et al. Phys. Rev. C* **47** (1993), 2571

LPI (Lebedev Physical Institute): $\gamma + {}^{12}\text{C} \rightarrow N + (A\text{-}\eta) \rightarrow N + \pi^+ + n + X$ and $\gamma + {}^{12}\text{C} \rightarrow N + (A\text{-}\eta) \rightarrow N + p + n + X$ ($A = {}^{11}$B or ^{11}C). The cross section of ^{11}B-η or ^{11}C-η production: $\sigma = 10\ \mu b$
G. A. Sokol, L. N. Pavlyuchenko. *Phys. At. Nucl.* **71** (2008), 809;
V. A. Baskov *et al.* arXiv:1212.6313 [nuclex] (2012)

JINR (Joint Institute for Nuclear Research): $d + {}^{13}\text{C} \rightarrow \pi + p + X$
S. V. Afanasiev *et al. Nucl. Phys. B Proc. Suppl.* **245** (2013), 173

COSY-GEM (FZ Jülich): $p + {}^{27}\text{Al} \rightarrow (\eta + {}^{25}\text{Mg}) + {}^{3}\text{He} \rightarrow ({}^{25}\text{Mg-}\eta)_{bound} + {}^{3}\text{He}$
$\|B_s = -13.3 \pm 1.64\ MeV$ i $\Gamma = 4.35 \pm 1.27\ MeV\|$; $\sigma = 0.46 \pm 0.16_{stat} \pm 0.06_{syst}\ nb$
A. Budzanowski *et al. Phys. Rev. C* **79** (2009), 012201

Search for light η-mesic nuclei

SPES-4, SPES-2 (SATURNE); ANKE, COSY-11 (COSY-Jülich): $dp(pd) \to {}^3\mathrm{He}\eta$

J. Berger *et al. Phys. Rev. Lett.* **61** (1988), 919

B. Mayer *et al. Phys. Rev. C* **53** (1996), 2068

T. Mersmann *et al. Phys. Rev. Lett.* **98** (2007), 242301

J. Smyrski *et al. Phys. Lett. B* **649** (2007), 258

H.-H. Adam *et al. Phys. Rev. C* **75** (2007), 014004

SPES-3, SPES-4 (SATURNE); ANKE, GEM (COSY-Jülich): $dd \to {}^4\mathrm{He}\eta$

R. Frascaria *et al. Phys. Rev. C* **50** (1994), R537

N. Willis *et al. Phys. Lett. B* **406** (1997), 14

A. Wrońska *et al. Eur. Phys. J. A* **26** (2005), 421

A. Budzanowski *et al. Nucl. Phys. A* **821** (2009), 193

MAMI/TAPS (Moguncja): $\gamma^3\mathrm{He} \to \pi^0 pX$

M. Pfeiffer *et al. Phys. Rev. Lett.* **92** (2004), 252001 ($B_s = -4.4\ MeV$; $\Gamma = 25.6\ MeV$)

F. Pheron *et al. Phys. Lett. B* **709** (2012), 21

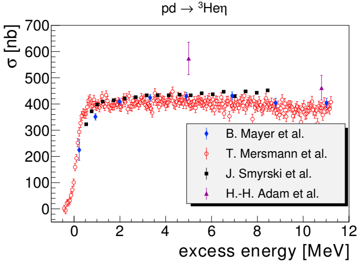
COSY-11, COSY-TOF: $dp \to ppp\pi^-$ $(\sigma_{upper} = 270\ nb)$;
$dp \to {}^3\mathrm{He}\pi^0$ $(\sigma_{upper} = 70\ nb)$

J. Smyrski *et al. Acta Phys. Pol. B Proc. Suppl.* **2** (2009), 133

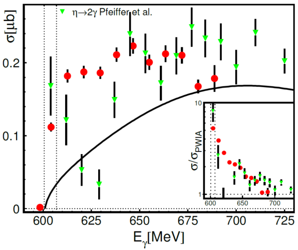
J. Smyrski *et al. Nucl. Phys. A* **790** (2007), 438

Production of η mesons

$dp(pd) \longrightarrow {}^3\mathrm{He}\eta$



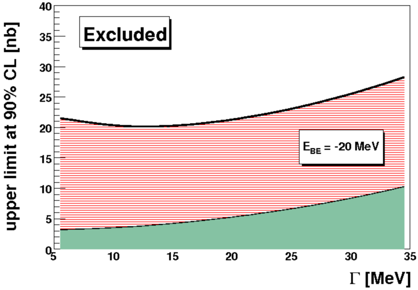
$\gamma^3\mathrm{He} \longrightarrow {}^3\mathrm{He}\eta$



F. Pheron *et al. Phys. Lett. B* **709** (2012), 21
M. Pfeiffer *et al. Phys. Rev. Lett.* **92** (2004), 252001

The extremely steep rise of the total cross section for the $dp(pd) \longrightarrow {}^3\mathrm{He}\eta$ reaction in the very close-to-threshold region followed by a plateau may originate from a pole of $\eta^3\mathrm{He} \longrightarrow \eta^3\mathrm{He}$ scattering amplitude in the complex excess energy plane Q with $\mathfrak{Im}\ Q < 0$. A steep increase of the total cross section for ${}^3\mathrm{He}\eta$ photo-production at the threshold via the $\gamma^3\mathrm{He} \longrightarrow {}^3\mathrm{He}\eta$ reaction shows that the rise of the cross section above threshold is independent of the initial channel and can therefore be assigned to the ${}^3\mathrm{He}$-η interaction.
C. Wilkin *et al. Phys. Lett. B* **654** (2007), 92

WASA-at-COSY: $dd \to {}^3\text{He}p\pi^-$ (2008)



$$\sigma_{upp}^{CL=90\%} \in (20, 27) \; nb$$

P. Adlarson *et al. Phys. Rev. C* **87** (2013), 035204

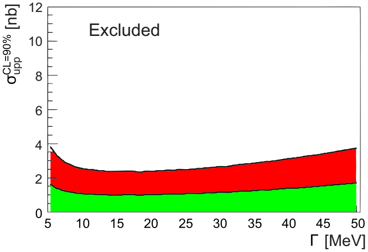
Predictions for the $dd \to ({}^3\text{He}\eta)_{bound} \to {}^3\text{He}p\pi^-$ reaction:

$$\sigma = 4.5 \; nb$$

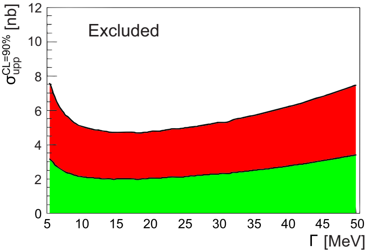
S. Wycech, W. Krzemień. *Acta. Phys. Polon. B* **45** (2014), 745

WASA-at-COSY: $dd \to {}^3\mathrm{He}n\pi^0$ i $dd \to {}^3\mathrm{He}p\pi^-$ (2010)

$dd \to {}^3\mathrm{He}n\pi^0$



$dd \to {}^3\mathrm{He}p\pi^-$



$$\sigma_{upp}^{CL=90\%} \in (2.5, 3.5)\ nb$$

$$\sigma_{upp}^{CL=90\%} \in (5, 7)\ nb$$

P. Adlarson *et al. Nucl. Phys. A* **959** (2017), 102

WASA-at-COSY: experiment 2014

Two hypotheses of the decay of η-mesic bound state:

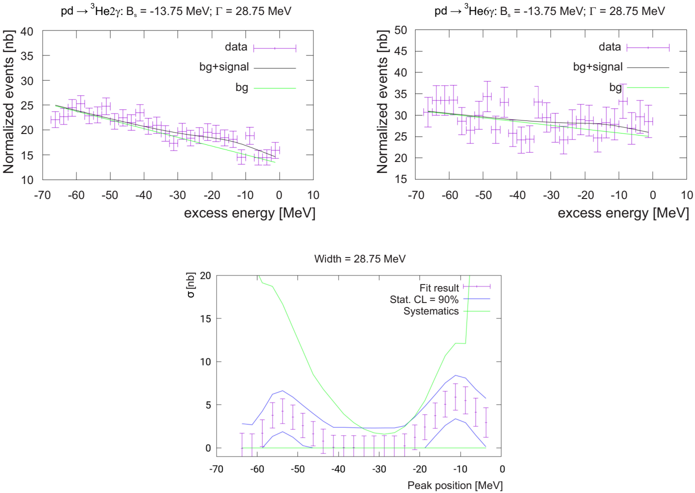
- absorption of the η meson and excitation of one of the nucleons to an $N^*(1535)$ resonance, which subsequently decays into a nucleon-pion pair:

$$\begin{aligned} pd \to ({}^3\text{He-}\eta)_{bound} &\to dp\pi^0 \to dp\gamma\gamma, \\ &\to dn\pi^+, \\ &\to ppn\pi^0 \to ppn\gamma\gamma, \\ &\to ppp\pi^-, \\ &\to pnn\pi^+. \end{aligned}$$

- decay of the η meson while "orbiting" around a nucleus:

$$\begin{aligned} pd \to ({}^3\text{He-}\eta)_{bound} &\to {}^3\text{He}2\gamma, \\ &\to {}^3\text{He}3\pi^0 \to {}^3\text{He}6\gamma. \end{aligned}$$

Direct decay of the bound η meson



$$\sigma_{upp}^{CL=90\%} \in (2, 15)\ nb$$