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

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for WASA-at-COSY Collaboration

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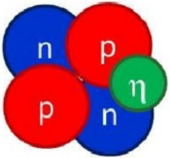
η-mesic nucleus

^4He-η



strong interaction

$$m_{bound} = m_{^4He} + m_{\eta} - B_s$$

meson

$u\bar{u}$, $d\bar{d}$, $s\bar{s}$

m_η=547.86 MeV
Γ=1.31 keV
$t=10^{-18}$s

$|Re(a_{\eta N})| > Im(a_{\eta N})$

attraction>absorption

Introduction – η-mesic nuclei

Attractive and strong interaction between η and nucleon

R. Bhalerao, L. C. Liu, Phys. Lett. B54, 685 (1985)

$\Downarrow$

Possible existence of η-mesic bound states postulated for atomic nuclei with A>12

Q. Haider, L. C. Liu, Phys. Lett. B172, 257 (1986)

Recent theoretical studies of hadronic- and photoproduction of η meson support the existence of light η-mesic nuclei like $(^3\text{He-}\eta)_{bound}$ $(^4\text{He-}\eta)_{bound}$

$B_s \in (1, 40)$ MeV, $\Gamma \in (1, 45)$ MeV

$dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$: σ=**4.5 nb** | $pd \to (^3\text{He-}\eta)_{bound} \to Xp\pi^-$: σ=**80 nb**

J.-J. Xie et al., Eur. Phys. J. A55 no.1, 6 (2019)
J.-J. Xie et al., Phys. Rev. C95, 015202 (2017)
N. Ikeno et al., Eur. Phys. J. A53 no. 10, 194 (2017)
A. Gal, B. Bazak, E. Friedman, Acta Phys. Pol. B48, 1781 (2017)
V. Metag, M. Nanova, E. Paryev, Prog. Part. Nucl. Phys. 97, 199 (2017)
N. G. Kelkar, Eur. Phys. J. A52 no.10, 309 (2016)
N. Barnea, E. Friedman, A. Gal, Phys. Lett B747, 345 (2015); Nucl. Phys. A 968 (2017)
S. Wycech, W. Krzemien, Acta. Phys. Polon B45, 745 (2014)
E. Friedman, A. Gal, J. Mares, Phys. Lett B725, 334 (2013)
C. Wilkin, Acta. Phys. Pol. B45, 603 (2014)
P. C. Bruns, A. Cieply, arXiv:1903.103; || M. Skurzok, S. Hirenzaki et al., arXiv:1908.03429

Status of the search for η-mesic Helium at WASA

<u>$(^4\text{He-}\eta)_{bound}$</u>

- **2008**: $dd \rightarrow {}^3\text{He}p\pi^-$ reaction

  P. Adlarson et al., Phys. Rev. C87, 035204 (2013)

- **2010**: $dd \rightarrow {}^3\text{He}n\pi^0$ and $dd \rightarrow {}^3\text{He}p\pi^-$ reactions

  P. Adlarson et al., Nucl. Phys. A 959, 102-115 (2017)

  M. Skurzok, P. Moskal, et al., Phys. Lett. B782, 6-12 (2018)

$\Uparrow$

η meson absorption and excitation of one of the nucleons to an N^* resonance, which subsequently decays into an N - π pair

<u>$(^3\text{He-}\eta)_{bound}$</u>

- **2014**:

  - $pd \rightarrow {}^3\text{He}2\gamma({}^3\text{He}6\gamma)$ reactions

    O. Rundel, PhD Thesis (2018), *arxiv:1905.04544*

    decay of the η - meson while it is still "orbiting" around a nucleus

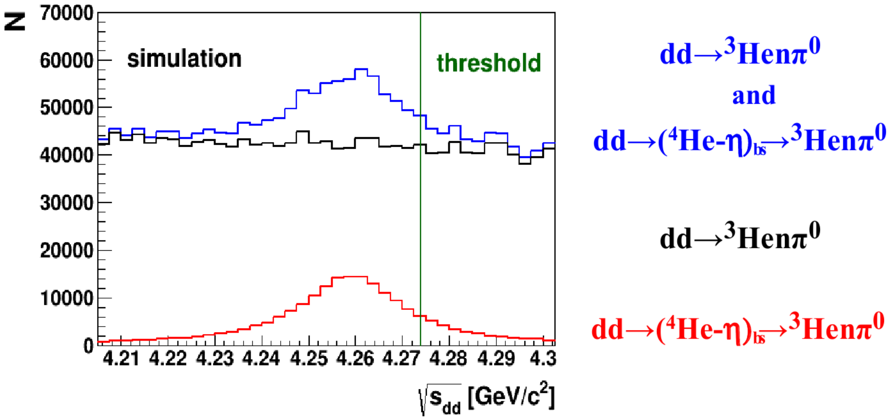
  - $pd \rightarrow ppp\pi^-(ppn\pi^0, dp\pi^0)$ reactions

    A. Khreptak, <u>Analysis in progress</u>

    Talk

η meson absorption and excitation of one of the nucleons to an N^* resonance, which subsequently decays into an N - π pair

Experimental method

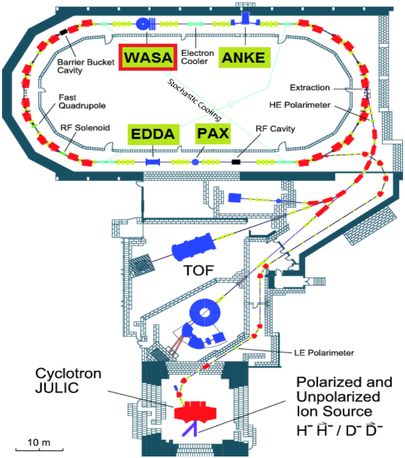


Excitation function

$(^4$He-$\eta)_{bound}$ existence manifested by resonant-like structure below η production threshold

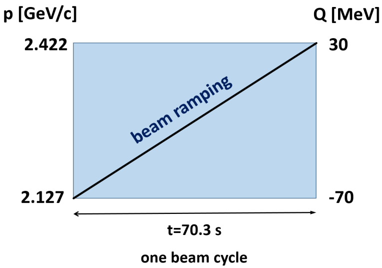
Exp. 186.1 & 186.2, FZ Jülich, Germany, 2008 and 2010

P. Moskal, W. Krzemien, J. Smyrski, *COSY proposal No. 186.1 & 186.2*



$dd \rightarrow {}^3\text{He}n\pi^0 \mid dd \rightarrow {}^3\text{He}p\pi^-$

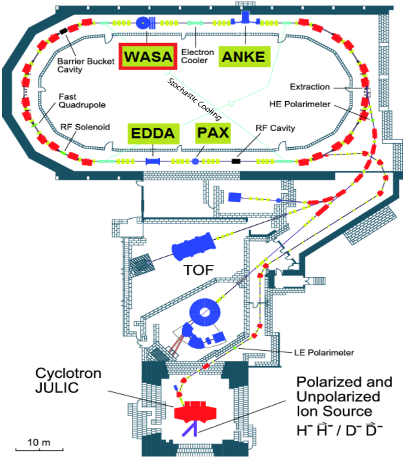
- **Measurement** with the **deuteron** beam momentum ramped and with the **deuteron** pellet target



- **Data** were effectively taken with high acceptance (58%)

Exp. 186.3, FZ Jülich, Germany 2014

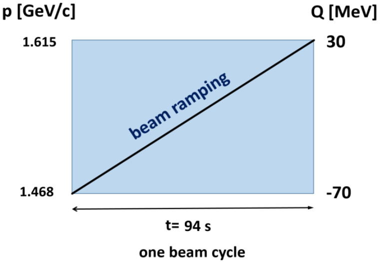
P. Moskal, W. Krzemien, M. Skurzok, *COSY proposal No. 186.3*



$pd \to ppp\pi^-(ppn\pi^0, dp\pi^0)$

$pd \to {}^3\mathbf{He}2\gamma\ ({}^3\mathbf{He}6\gamma)$

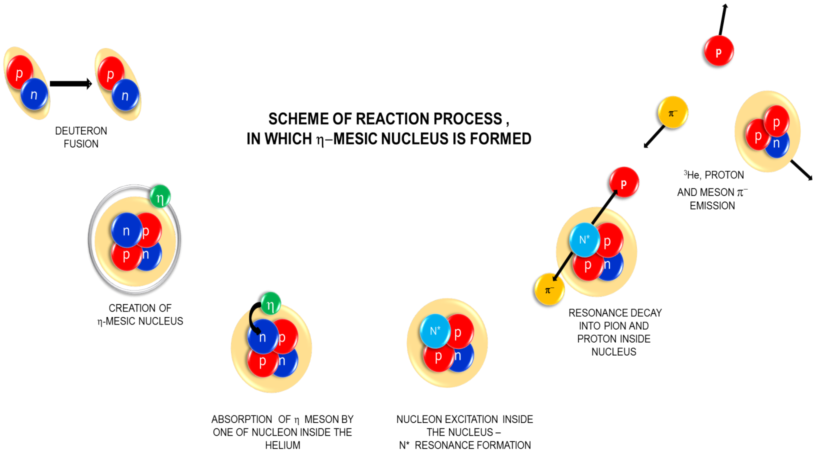
- **Measurement** with the **proton** beam momentum ramped and with the **deuteron** pellet target



- **Data** were effectively taken with high acceptance

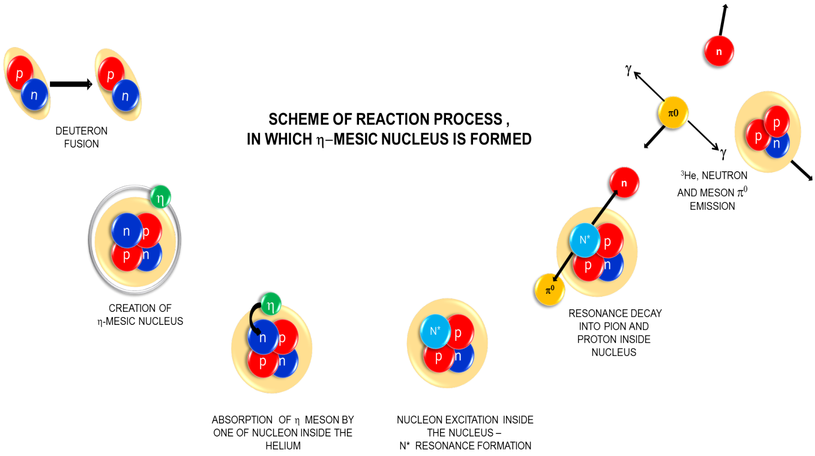
Kinematical mechanism of the reaction (via N^*)

$$dd \rightarrow ({}^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^-$$



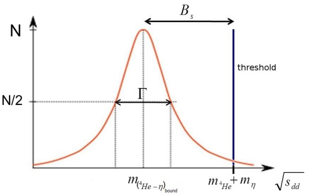
Kinematical mechanism of the reaction (via N^*)

$$dd \rightarrow ({}^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}n\pi^0$$



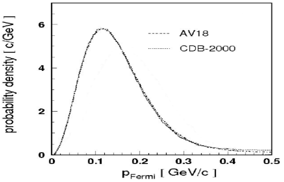
Simulation of $(^4\text{He-}\eta)_{bound}$ production and decay

Breit-Wigner distribution



$$N\left(\sqrt{s_{dd}}\right) = \frac{1}{2\pi}\frac{\Gamma^2/4}{\left(\sqrt{s_{dd}}-m_{(^4He-\eta)_{bound}}\right)^2+\Gamma^2/4}$$

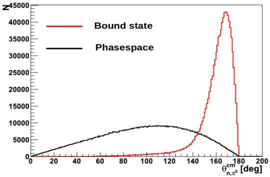
Spectator Model



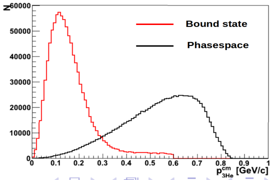
$$|\mathbb{P}_{^3He}|^2 = m^2_{^3He}$$

$$\eta + N \Rightarrow N^*(1535) \Rightarrow N + \pi = \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$$

- relative N-π angle in the CM: $\theta_{cm}^{N,\pi} \sim 180^\circ$

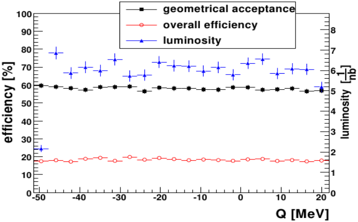


- low ^{3}He momentum in the CM

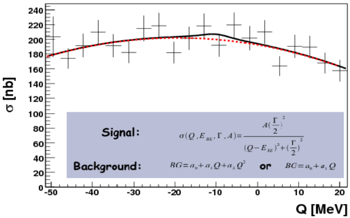


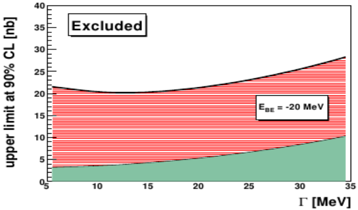
Experiment-May 2008

- **Channel:** $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ (norm: $dd \rightarrow {}^3\text{He}n$)
- **Measurement:** beam momentum ramped from **2.185GeV/c to 2.400GeV/c** $\Rightarrow$ the range of excess energy **Q∈(-51,22)MeV**
- **Luminosity:** $L = 118 \frac{1}{nb}$
- **Acceptance:** A=53%



Excitation function





P. Adlarson et al., Phys. Rev. C87 (2013), 035204
W. Krzemien, Ph. D Thesis, Jagiellonian University (2012)

RESULT: $\sigma_{dd\rightarrow(^4He-\eta)_{bound}\rightarrow {}^3He p\pi^-} < 27\ nb$

Experiment-Nov/Dec 2010

- **Channels:** $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$
  $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$
  (norm: $dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)
- **Measurement:** beam momentum ramped from **2.127GeV/c to 2.422GeV/c** $\Rightarrow$ the range of excess energy **Q∈(-70,30)MeV**
- **Luminosity:** $L=1200\frac{1}{nb}$
- **Acceptance:** A=53%

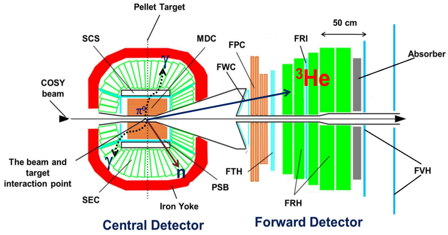
$\Downarrow$

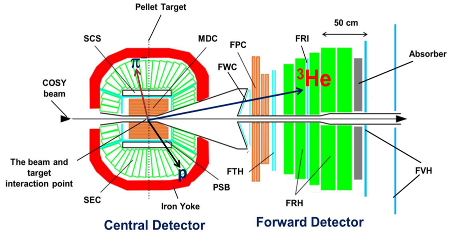
about 10 times higher statistics than in 2008

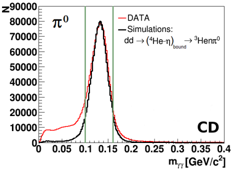
ANALYSIS:

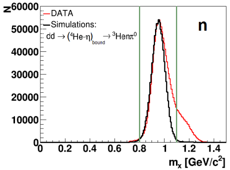
- Particles identification
- Selection bound state region
- Determination of excitation functions
- Determination the upper limit of the total cross section

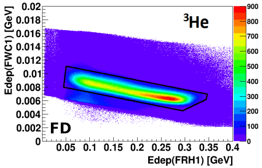
Search for $(^4\text{He-}\eta)_{bound}$ in $dd \rightarrow {}^3\text{He}N\pi$ reaction | PID

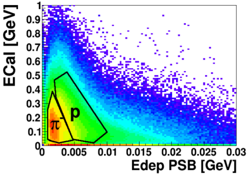


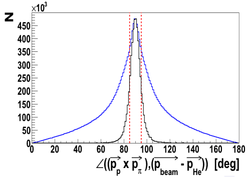




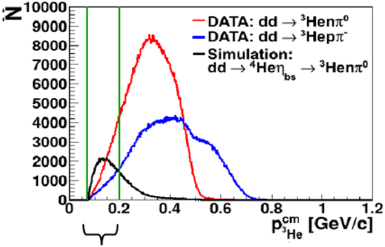




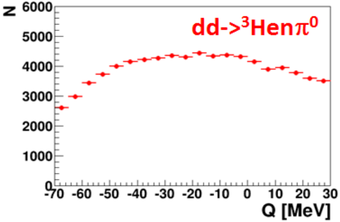


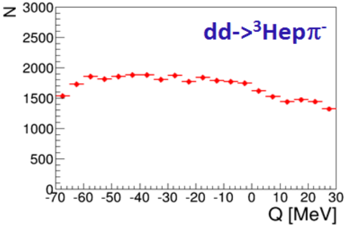


Search for $(^4\text{He-}\eta)_{bound}$ | Selection criterium



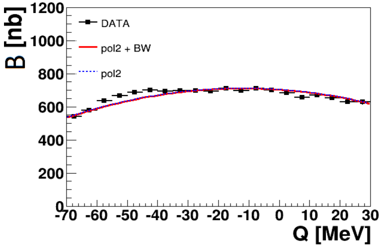
region rich in signal



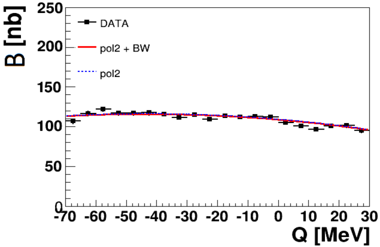


Determination of the upper limit of the total cross section for $dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}N\pi$ processes at CL=90%

$dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$ $\Downarrow$



$dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$ $\Downarrow$



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

Breit-Wigner (signal) + pol2 (background)

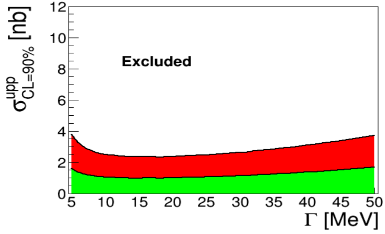
taking into account the **isospin relation** between the both of the considered channels:

$$P(N^* \to p\pi^-)=2P(N^* \to n\pi^0)$$

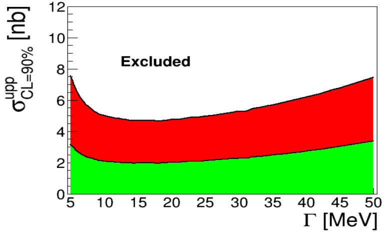
B_s,Γ - fixed parameters | A, B, C, D - free parameters || $\sigma^{upp}_{CL=90\%} = k \cdot \sigma_A$, k=1.64 (for CL=90%)

Determination of the upper limit of the total cross section for $dd \rightarrow (^4He\text{-}\eta)_{bound} \rightarrow {}^3He p \pi^-$ process at CL=90%

$\sigma^{upp}_{CL=90\%}$ for
$dd \rightarrow (^4He\text{-}\eta)_{bound} \rightarrow {}^3He n \pi^0$
$\Downarrow$



$\sigma^{upp}_{CL=90\%}$ for
$dd \rightarrow (^4He\text{-}\eta)_{bound} \rightarrow {}^3He p \pi^-$
$\Downarrow$



RESULT:
$\sigma_{dd \rightarrow (^4He-\eta)_{bound} \rightarrow {}^3He n \pi^0} < 3.5\ nb$

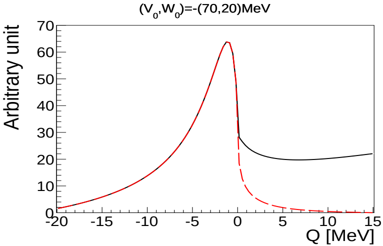
RESULT:
$\sigma_{dd \rightarrow (^4He-\eta)_{bound} \rightarrow {}^3He p \pi^-} < 7\ nb$
2008: $\sigma < 27\ nb$

More details in: P. Adlarson et al., Nucl. Phys. A 959, 102-115 (2017)

Comparison with N. Ikeno et al. model prediction

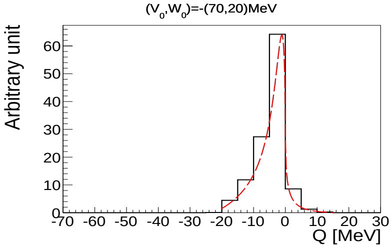
N. Ikeno, H. Nagahiro, D. Jido, S. Hirenzaki, Eur. Phys. J. A 53, 194 (2017)

- total cross sections for the $dd \rightarrow ({}^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}N\pi$ reaction determined based on phenomenological calculations
- the model reproduced the data on the $dd \rightarrow {}^4\text{He}\,\eta$ reaction quite well
- $\sigma = \sigma_{conv} + \sigma_{esc}$
- σ_{conv} - determined for different parameters V_0 and W_0 of a spherical η-^{4}He optical potential $V(r) = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_\alpha(0)}$ (the total cross section in the subthreshold excess energy region where the η meson is absorbed by the nucleus)
- normalization in the sense that the escape part reproduces the measured cross sections for the $dd \rightarrow {}^4\text{He}\eta$ process



σ —

σ_{conv} - -

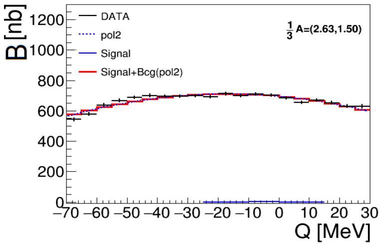


σ_{conv} spectrum convoluted with the experimental resolution functions

Comparison with N. Ikeno et al. model prediction

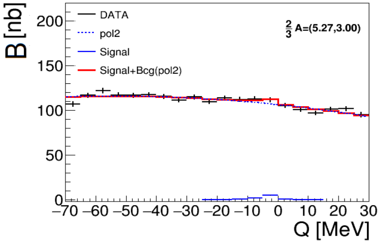
$dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}n\pi^0$

$\Downarrow$



$dd \to (^4\text{He-}\eta)_{bound} \to {}^3\text{He}p\pi^-$

$\Downarrow$



$$\sigma_{n\pi^0}(Q) = \frac{1}{3}A \cdot Theory(Q) + B_1Q^2 + C_1Q + D_1$$

$$\sigma_{p\pi^-}(Q) = \frac{2}{3}A \cdot Theory(Q) + B_2Q^2 + C_2Q + D_2$$

isospin relation between the both of the considered channels

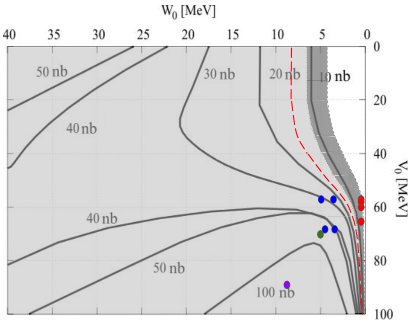
Theory(Q) - theoretical function after binning with the amplitude normalized to unity
$B_{1,2}Q^2 + C_{1,2}Q + D_{1,2}$ - polynomial of the second order

Fit performed for theoretical spectra obtained for different optical potential parameters (V_0, W_0)

Comparison with N. Ikeno et al. model prediction

results obtained for different optical potential parameters (V_0, W_0)

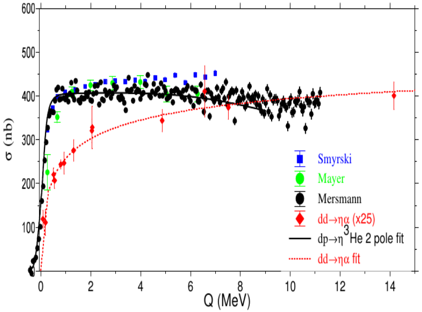
V_0	W_0	A (fit) [nb]	$\sigma_{upp}^{CL=90\%}$ [nb]
-30	-5	-5.0±3.9	6.5
-30	-20	-2.2±3.5	5.8
-30	-40	0.2±3.8	6.3
-50	-5	0.1±3.8	6.3
-50	-20	3.3±4.1	6.8
-50	-40	6.0±4.2	6.9
-70	-5	6.4±4.5	7.4
-70	-20	7.9±4.5	7.4
-70	-40	7.5±3.7	6.1
-100	-5	6.3±4.5	7.4
-100	-20	6.9±3.9	6.4
-100	-40	5.3±3.1	5.2



Contour plot of the theoretically determined conversion cross section in $V_0 - W_0$ plane.

The allowed parameter space ($|V_0| < \sim$ 60 MeV and $|W_0| < \sim$ 7 MeV) excludes most optical model predictions of $\eta -{}^4$He nuclei except for some loosely bound narrow states.

More details in: **M. Skurzok, P. Moskal, et al., Phys. Lett. B708, 6-12 (2018)**



$$\sigma_{pd\rightarrow^3He-\eta} \approx 25\sigma_{dd\rightarrow^4He-\eta}$$

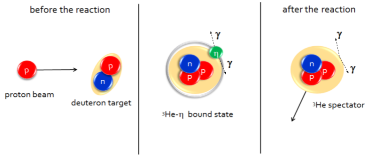
About 2 weeks of measurement
$(L \approx 2500\frac{1}{nb})$

Measurement: p_{beam} : 1.468-1.615GeV/c, **Q∈(-70,30)MeV**

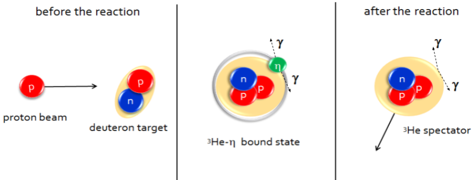
Channels:

- **Via the resonance decay** N^***:**
  1) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppp\pi^-$
  2) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow ppn\pi^0$
  3) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow dp\pi^0$
  Aleksander Khreptak → Talk

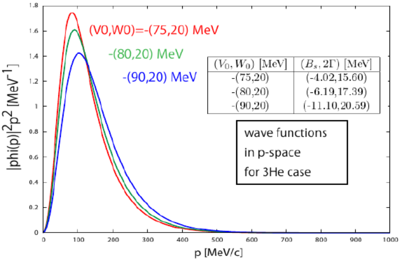
- **Absorption of orbiting** η
  4) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\ 2\gamma$
  5) $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}\ 6\gamma$



Simulation of $(^3\text{He-}\eta)_{bound}$ production and decay



- **^{3}He is spectator** $|\mathbb{P}_{^3He}|^2 = m^2_{^3He}$
- **Fermi momentum distribution of the η meson in ^{3}He-η bound system**



- **bound η decays to 2γ or $3\pi^0$**

Structure of hypothetical ^{3}He-η bound state can be described as a solution of Klein-Gordon equation:

$$\left[-\vec{\nabla}^2 + \mu^2 + 2\mu U_{opt}(r)\right]\psi(\vec{r}) = E^2_{KG}\psi(\vec{r})$$

where: E_{KG} - Klein -Gordon energy, μ - ^{3}He-η reduced mass,

optical potential:

$$U_{opt}(r) = (V_0 + iW0)\frac{\rho(r)}{\rho_0}$$

where: $\rho(r)$ - density distr. for ^{3}He, ρ_0 - normal nuclear density

KG equation solved for several sets of (V_0, W_0)

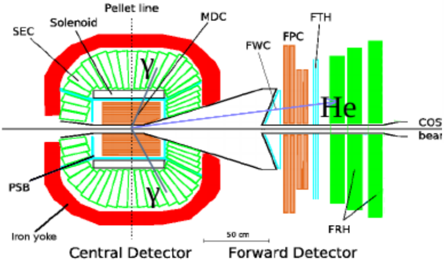
$$\Downarrow$$

$$E_{KG},\ \psi(\vec{r})$$

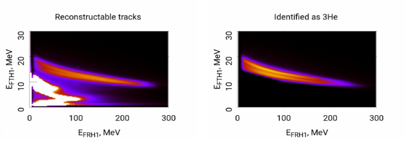
$\rightarrow$ **M. Skurzok, S. Hirenzaki, arxiv:1908.03429, accepted in NPA**

Search for $(^3He\text{-}\eta)_{bound}$ | Selection criteria

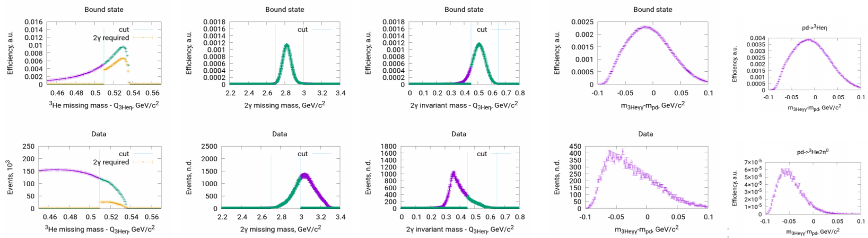
$$pd \to (^3He\eta)_{bound} \to ^3He2\gamma$$



Require ^3He track in Forward Detector

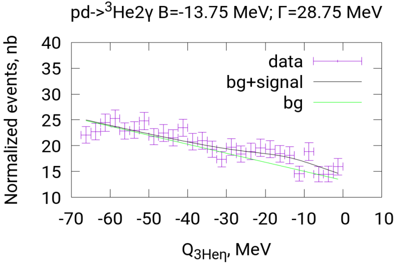


and two γ tracks in Central Detector

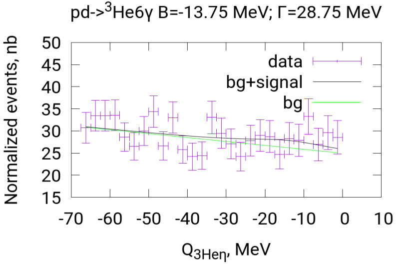


Determination of the upper limit of the total cross section for $pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}2\gamma(6\gamma)$ processes at CL=90%

$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}2\gamma$ $\Downarrow$



$pd \rightarrow (^3\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}6\gamma$ $\Downarrow$



simultaneous fit with $P_{\eta decay} \frac{A \cdot \Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4} + BQ + C$

Breit-Wigner (signal) + pol2 (background)

where $P_{\eta decay}$ are branching ratios for η decays:
$P_{\eta\rightarrow 2\gamma}$=0.3941, $P_{\eta\rightarrow 3\pi^0}$=0.3268

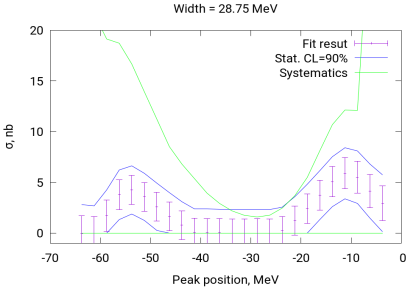
B_s,Γ - fixed parameters | A, B, C - free parameters || $\sigma^{upp}_{CL=90\%} = A + k \cdot \sigma_A$, k=1.64 (for CL=90%)

Determination of the upper limit of the total cross section for $pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$ process at CL=90%

$\sigma^{upp}_{CL=90\%}$ for

$pd \to (^3\text{He-}\eta)_{bound} \to {}^3\text{He}2\gamma(6\gamma)$

$\Downarrow$



PRELIMINARY

slight indication of the signal from the bound state for $\Gamma > 20$ MeV and $B_s \in (015)$ MeV

$\Downarrow$

However, the observed indication is within the range of the systematic error

$\Downarrow$

we cannot make a definite conclusion here on possible bound state formation

RESULT:

$\sigma_{pd\to(^3He-\eta)_{bound}\to ^3He2\gamma(6\gamma)} < 15\ nb$

Previous result:

COSY-11

$\sigma_{pd\to(^3He-\eta)_{bound}\to ^3He\pi^0} < 70\ nb$

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

More details in: O. Rundel, PhD Thesis (2018), arxiv:1905.04544

Summary of the search for η-mesic Helium at WASA

$(^4He\text{-}\eta)_{bound}$

- **2008**: $dd \rightarrow {}^3He p \pi^-$ reaction

$\sigma_{dd\rightarrow(^4He-\eta)_{bound}\rightarrow ^3He p\pi^-} < 27\ nb$

- **2010**: $dd \rightarrow {}^3He n \pi^0$ and $dd \rightarrow {}^3He p \pi^-$ reactions

$\sigma_{dd\rightarrow(^4He-\eta)_{bound}\rightarrow ^3He p\pi^-} < 7\ nb$

$\sigma_{dd\rightarrow(^4He-\eta)_{bound}\rightarrow ^3He n\pi^0} < 3.5\ nb$

$(^3He\text{-}\eta)_{bound}$

- **2014**: $pd \rightarrow {}^3He 2\gamma$ and $pd \rightarrow {}^3He 6\gamma$ reactions

$\sigma_{dp\rightarrow(^3He-\eta)_{bound}\rightarrow ^3He 2\gamma(6\gamma)} < 15\ nb$

PRELIMINARY

- **2014**: $pd \rightarrow ppp\pi^-(ppn\pi^0, dp\pi^0)$ reactions

A. Khreptak,

Analysis in progress

Talk

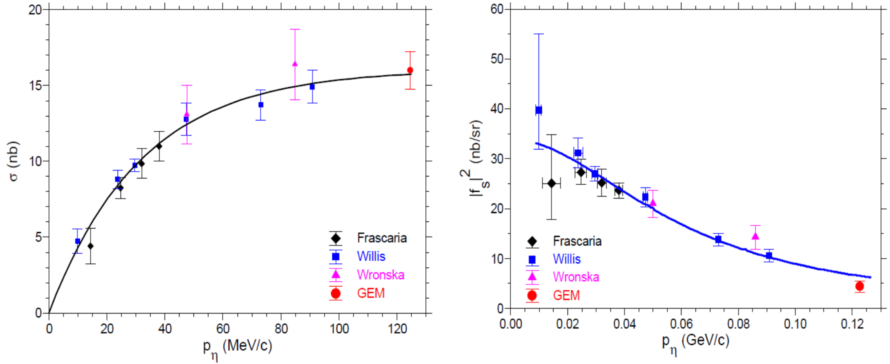
Summary and Conclusions

- Search for η-mesic helium was carried out using the ramped beam technique.
- No bound state signal visible in 2008 data (upper limit of the total cross section for the bound state production determined)
- 2010 measurement doesn't show a narrow signal of η-mesic nuclei in $dd \rightarrow {}^3\text{He}n\pi^0$ and $dd \rightarrow {}^3\text{He}p\pi^-$ channels
- 2014 measurement doesn't show a narrow signal of η-mesic nuclei in $pd \rightarrow {}^3\text{He}2\gamma$ and $pd \rightarrow {}^3\text{He}6\gamma$ channels
- The upper limits for $dd \rightarrow ({}^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ and $dd \rightarrow ({}^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$reaction in order of **few nb**!
- The upper limits for $pd \rightarrow {}^3\text{He}2\gamma(6\gamma)$ reactions $<$ **15 nb**!
- Analysis in progress for $pd \rightarrow ppp\pi^-(ppn\pi^0, dp\pi^0)$ channels

Thank you for attention

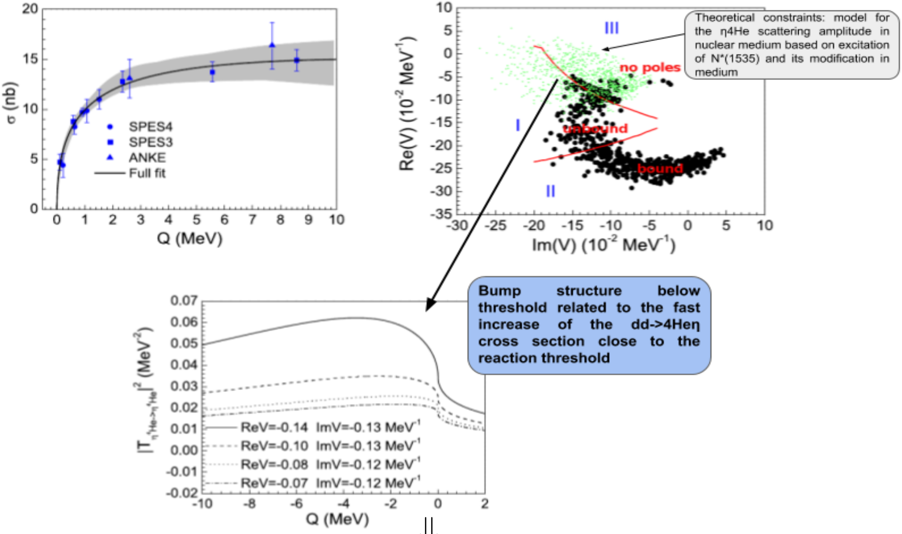
Exp. indications of the existence of the ^{4}He-η bound state

total cross section $dd \to {}^4\text{He-}\eta$ $\quad |f_s|^2 = \frac{p_d}{p_\eta}\frac{\sigma}{4\pi}$



R. Frascaria et al., Phys. Rev. C50, 573 (1994)
N. Willis et al., Phys. Lett. B406, 14 (1997)
A. Wronska et al., Eur. Phys. J. A26, 421428 (2005)
A. Budzanowski et al., Nucl. Phys. A821, 193 (2009)

Exp. indications of the existence of the ^{4}He-η bound state

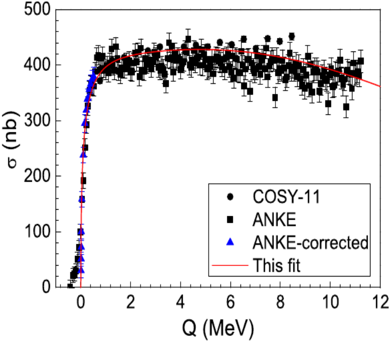


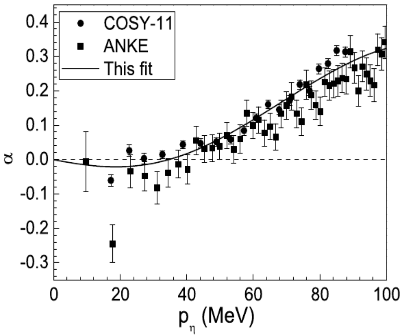
$\Downarrow$

J.-J. Xie et al., Eur. Phys. J. A55 no.1, 6 (2019)

Exp. indications of the existence of the ^{3}He-η bound state

total cross section $pd \to {}^3\text{He-}\eta$ $\frac{d\sigma(\theta_\eta)}{d\Omega} = \frac{\sigma_{tot}}{4\pi}(1 - \alpha cos\theta_\eta)$



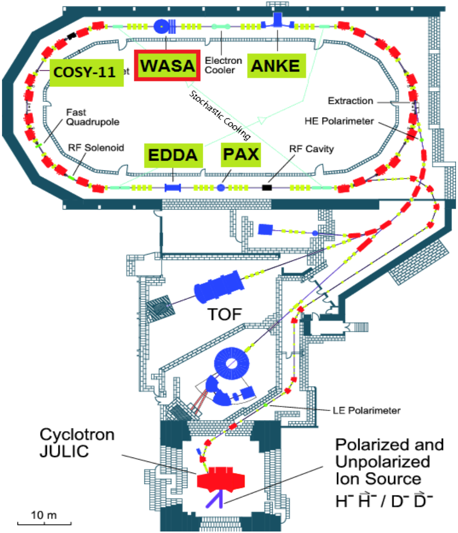


$\Downarrow$

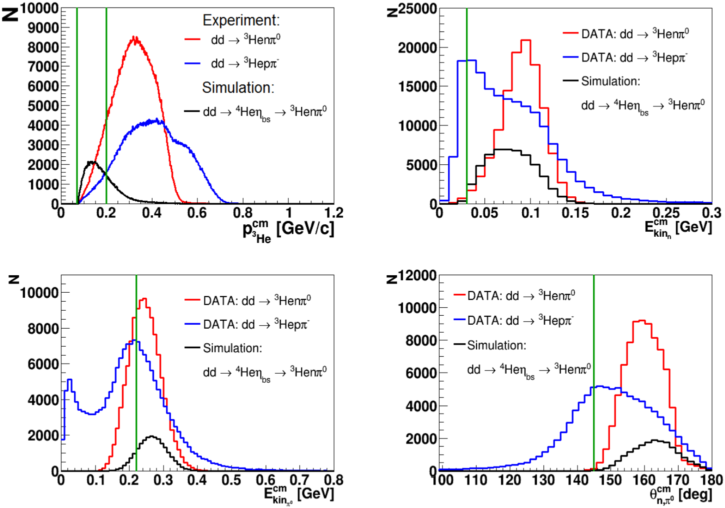
J.-J. Xie, et al., Phys. Rev. C 95, 015202 (2017)

"weakly bound ^{3}He-η state with **binding energy** *of the order of* **0.3 MeV** *and a* **width** *of the order of* **3 MeV***"*, $a_{\eta 3He} = [(2.23 \pm 1.29) - i(4.89 \pm 0.57)]$ *fm*

COoler SYnchrotron COSY



- 184 m circumference cooler synchrotron
- Polarized and unpolarized proton and deuteron beam
- Momentum range 0.3 - 3.7 GeV/c
- Stochastic and electron cooling
- 10^{11} particles in ring - luminosities 10^{31} - 10^{32} $cm^{-2}s^{-1}$
- Ramped beam (search for η-mesic nuclei)



DATA: $dd \rightarrow {}^3\text{He}p\pi^-$

DATA: $dd \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$

Signal: $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$

Cross section

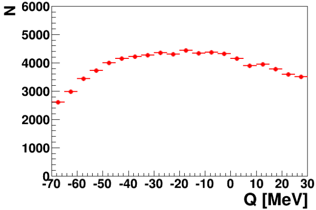
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

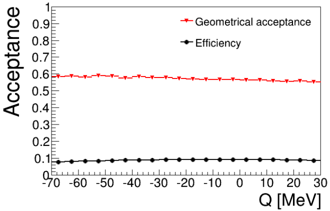
ϵ - full detection efficiency

Excitation function



Efficiency

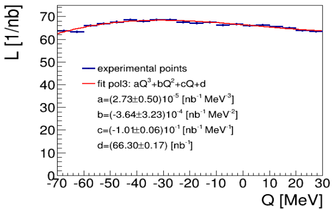
$dd \rightarrow ({}^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$



from simulations: $\epsilon = \frac{N_{acc}}{N_{gen}}$

Integrated luminosity

$dd \rightarrow ppn_{sp}n_{sp}$



$dd \rightarrow ppn_{sp}n_{sp}$: L=$(1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm})nb^{-1}$

$dd \rightarrow {}^3\mathrm{He}n$: L=$(1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm})nb^{-1}$

Cross section

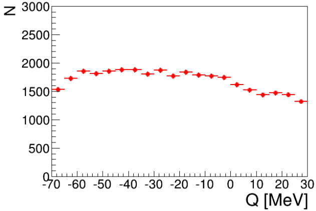
$$\sigma(Q) = \frac{N(Q)}{L(Q)\epsilon(Q)}$$

N - number of experimental events

L - integrated luminosity

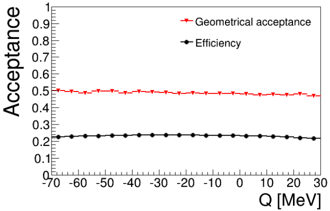
ϵ - full detection efficiency

Excitation function



Efficiency

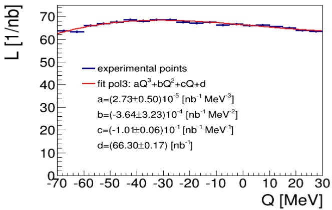
$dd \rightarrow ({}^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$



from simulations: $\epsilon = \frac{N_{acc}}{N_{gen}}$

Integrated luminosity

$dd \rightarrow ppn_{sp}n_{sp}$

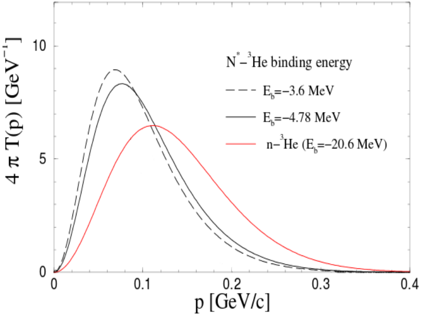


$dd \rightarrow ppn_{sp}n_{sp}$: $L = (1329 \pm 2_{stat} \pm 108_{syst} \pm 64_{norm})\, nb^{-1}$

$dd \rightarrow {}^3\text{He}n$: $L = (1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm})\, nb^{-1}$

Systematics

Main contribution: assumption that N^* resonance has a momentum distribution identical to the distribution of nucleons inside He



N^*-^3He momentum distribution determined by prof. Neelima G. Kelkar

The elementary $NN^* \to NN^*$ interaction was constructed within a π plus η meson exchange model and the N^* -nucleus potential was then obtained by folding the elementary NN^* interaction with a nuclear density. A couple of possible bound states of the N^* - 3He system, depending on the choice of the πNN^* and ηNN^* coupling constants were predicted.

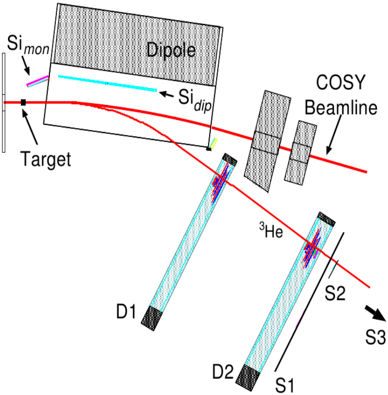
Details:

N. G. Kelkar, Eur. Phys. J. A 52 (2016) 309.

N. G. Kelkar, D. Bedoya Ferro, P. Moskal, Acta Phys. Pol. B 47 (2016) 299.

Search for $(^3\text{He-}\eta)_{bound}$ with COSY-11

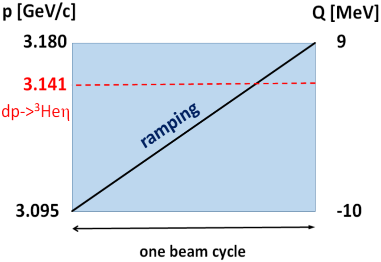
Exp. 142, FZ Jülich, Germany, 2005
P. Moskal, W. Krzemien, J. Smyrski,
COSY proposal No. 142 (2004)



$dp \to {}^3\mathbf{He}\pi^0 \mid dp \to ppp\pi^-$

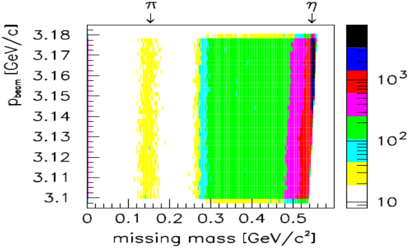
- **Measurement**
  -with the deuteron beam momentum varied continuously within each cycle from **3.095 - 3.180 GeV/c** crossing ^{3}Heη kinematic threshold at $p_{beam} = 3.141$ GeV/c

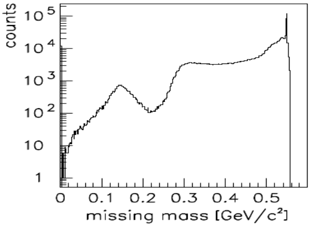
  -with the proton cluster target



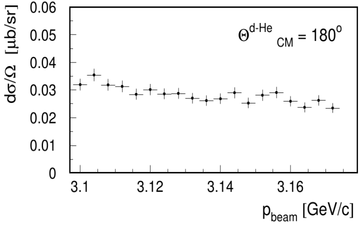
Search for $(^3\text{He-}\eta)_{bound}$ with COSY-11

$dp \to {}^3\mathbf{He}\pi^0$





- Luminosity determined using *dp* elastic scattering
- Excitation function

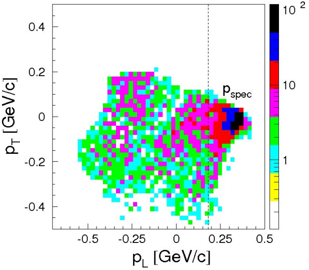


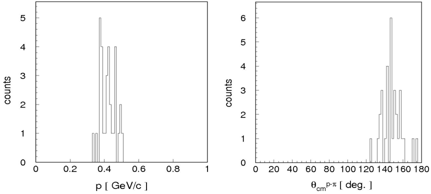
J. Smyrski et al., Nucl. Phys. A790, 438 (2007)

RESULT: $\sigma_{dp\to(^3He-\eta)_{bound}\to{}^3He\pi^0} < 70\ nb$

Search for $(^3He\text{-}\eta)_{bound}$ with COSY-11

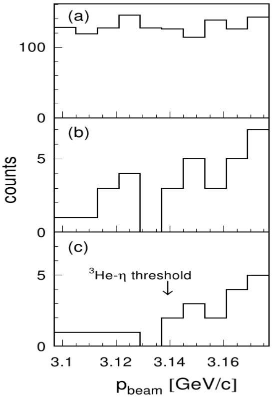
$dp \rightarrow ppp\pi^-$





W. Krzemien et al., Int. J. Mod. Phys. A24, 576 (2009)

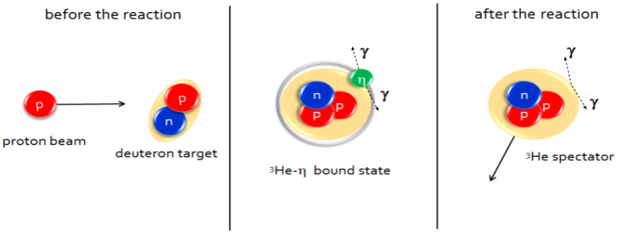
Excitation function

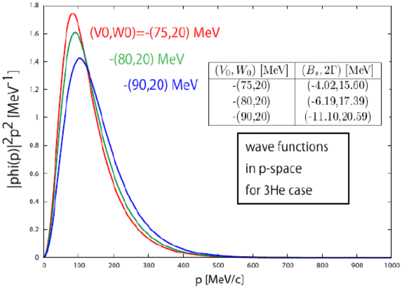


P. Moskal, J. Smyrski, Acta Phys. Polon. B41, 2281 (2010)

RESULT: $\sigma_{dp \rightarrow (^3He-\eta)_{bound} \rightarrow ppp\pi^-} < 270\ nb$

Analysis of $pd \rightarrow (^3\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}\ 2\gamma$ process



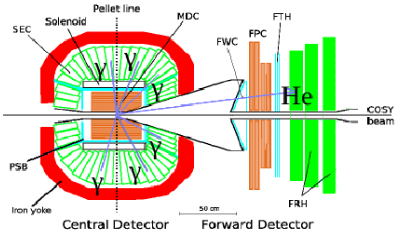


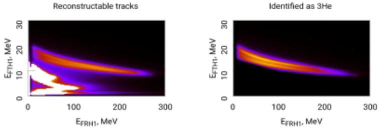
S. Hirenzaki, H. Nagahiro, Private communication (2016)

- ^{3}He spectator
- $P_{^3He}$: $p_{^3He} = \sqrt{m^2_{^3He} + p^2_{fermi}}$, distributed isotropically
- $P_{\eta_{bound}} = P_p + P_d - P_{^3He} \Rightarrow m_{\eta_{bound}} = |P_{\eta_{bound}}|$

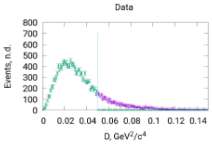
Search for $(^3\text{He-}\eta)_{bound}$ | Selection criteria

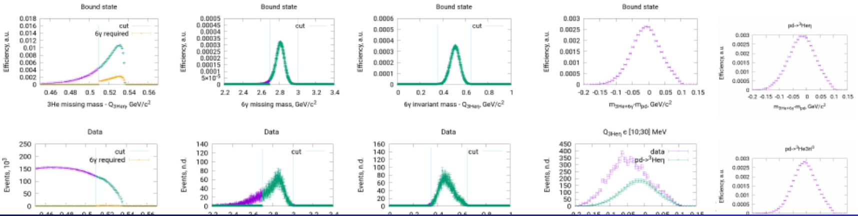
$$pd \rightarrow$$
$$(^3He\eta)_{bound} \rightarrow {}^3He3\pi^0 \rightarrow {}^3He6\gamma$$



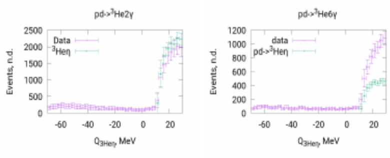


$$D = \sum_{i=1}^{3}(m_{\gamma_{(2i-1)}\gamma_{2i}} - m_{\pi^0})^2$$





Events count

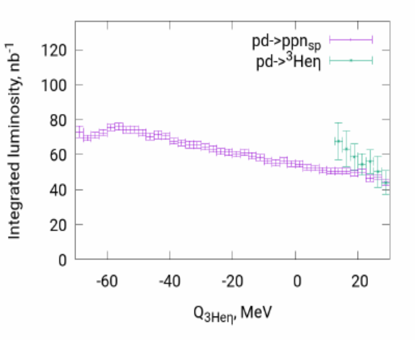


$$\sigma(Q_{^3He\eta}) = \frac{N(Q_{^3He\eta})}{L(Q_{^3He\eta})\epsilon(Q_{^3He\eta})}$$

$N(Q_{^3He\eta})$ - events count

$L(Q_{^3He\eta})$ - integrated luminosity

$\epsilon(Q_{^3He\eta})$ - registration efficiency



Normalized