Search for the ^{4}He-η bound state in $dd \rightarrow {}^3\text{He}n\pi^0$ and $dd \rightarrow {}^3\text{He}p\pi^-$ reactions with the WASA-at-COSY facility

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INFN LNS, Catania

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UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE
FNP Fundacja na rzecz Nauki Polskiej
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INTERNATIONAL PHD PROJECT IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

This project is supported by the Foundation for Polish Science-MPD program co-financed by the European Union within the European Regional Development Fund

Outline

Motivation

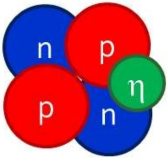
- Search for new kinds of nuclear matter
- Investigation of η interaction with nucleons inside a nuclear matter
- Study of N*(1535) properties in nuclear matter
  D. Jido, H. Nagahiro, S. Hirenzaki, Phys. Rev. C66, 045202 (2002)
  S. Hirenzaki et al., Acta Phys. Polon. B41, 2211 (2010)
- Information about η meson structure (contribution of the flavour singlet component of the quark-gluon wave function)
  S. D. Bass, A. W. Thomas, Phys. Lett. B634, 368 (2006)
  S. Hirenzaki, H. Nagahiro, Acta Phys.Polon. B45, 619 (2014)

η-mesic bound state

η-mesic nucleus

^4He-η

STRONG INTERACTION



$$B_s = \Delta mc^2$$

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

η-mesic bound state

Conditions for the existence of eta-mesic nuclei ⇒

$$\mathrm{Re}\, a_{\eta-nucleus} < 0$$

$$|\mathrm{Re}\, a_{\eta-nucleus}| > |\mathrm{Im}\, a_{\eta-nucleus}|$$

Attractive interaction between η and N

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

$$\Downarrow$$

possible existence of η-mesic bound state for A$>$12

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

η-mesic bound state

Recent theoretical investigations of hadronic- and photoproduction of η meson

$$0.18\,fm \leq \mathrm{Re}\, a_{\eta N} \leq 1.03\,fm$$

$$0.16\,fm \leq \mathrm{Im}\, a_{\eta N} \leq 0.49\,fm$$

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

$(^4\mathrm{He}\text{-}\eta)_{bs}$ $(\mathrm{T}\text{-}\eta)_{bs}$

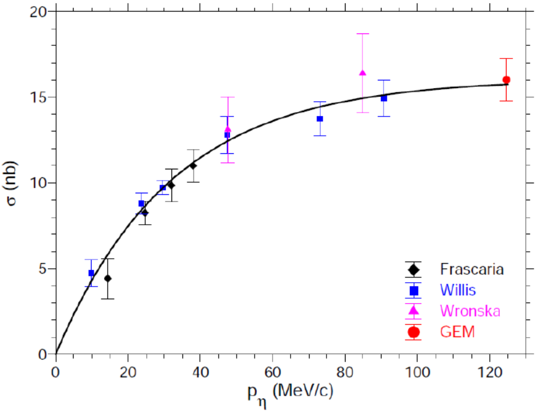
$(^3\mathrm{He}\text{-}\eta)_{bs}$ $(\mathrm{d}\text{-}\eta)_{bs}$

$dd \rightarrow (^4\mathrm{He}\text{-}\eta)_{bound} \rightarrow {}^3\mathrm{He}N\pi$: $B_s \sim$ MeV, half width 1-20 MeV, σ=**4.5 nb**

S. Wycech, W. Krzemien, Acta. Phys. Polon B45, 745 (2014)

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

$dd \to {}^4\text{He-}\eta$



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

Production of ^{4}He-η in dd collision

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

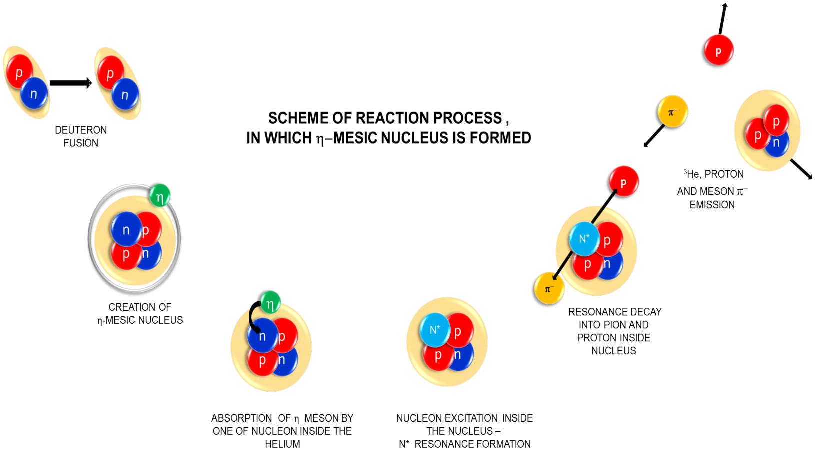
$$dd \rightarrow \left({}^4He-\eta\right)_{bs} \rightarrow {}^3He\ n\ \pi^0 \rightarrow {}^3He\ n\ \gamma\ \gamma$$

$$dd \rightarrow \left({}^4He-\eta\right)_{bs} \rightarrow d\ p\ p\ \pi^-$$

$$dd \rightarrow \left({}^4He-\eta\right)_{bs} \rightarrow T\ p\ \pi^0 \rightarrow T\ p\ \gamma\ \gamma$$

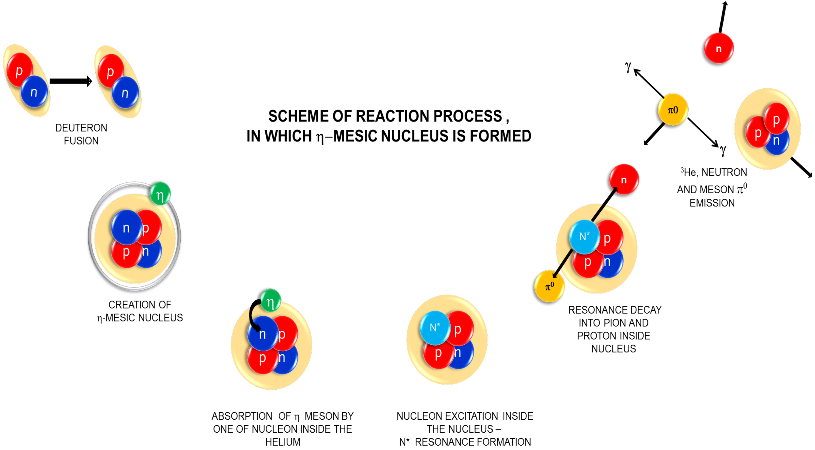
Kinematic mechanism of the reaction

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



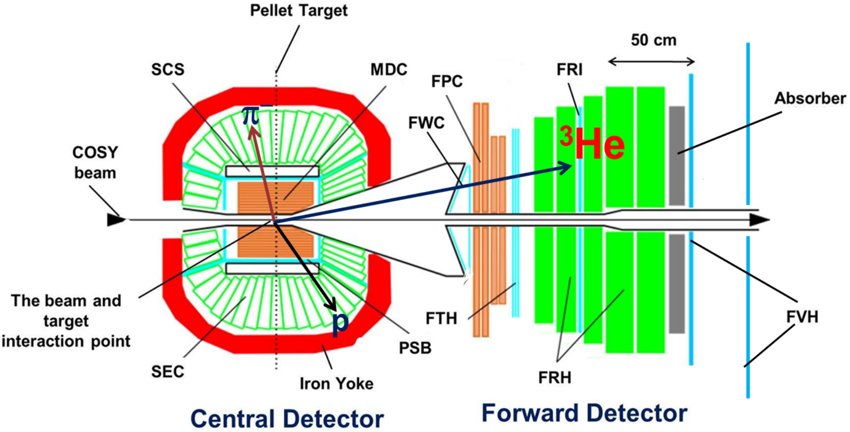
Kinematic mechanism of the reaction

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



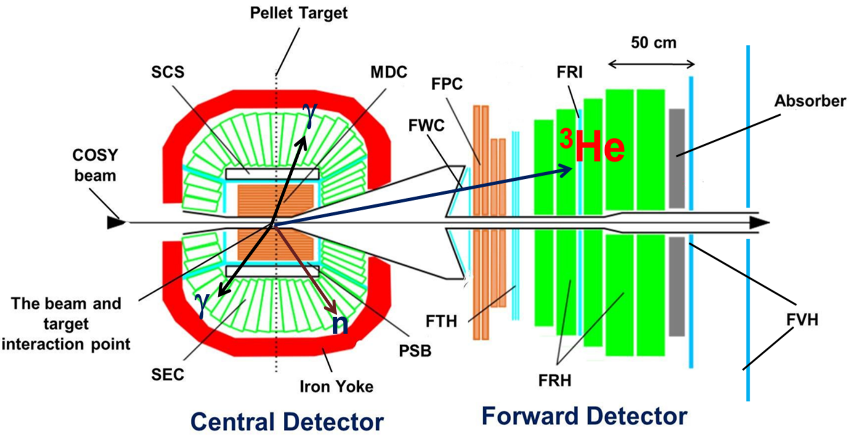
Search for η-mesic nuclei with WASA-at-COSY

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



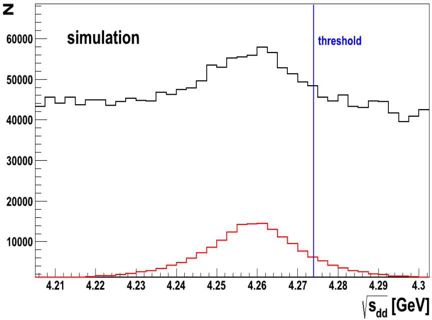
Search for η-mesic nuclei with WASA-at-COSY

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



Experimental method

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

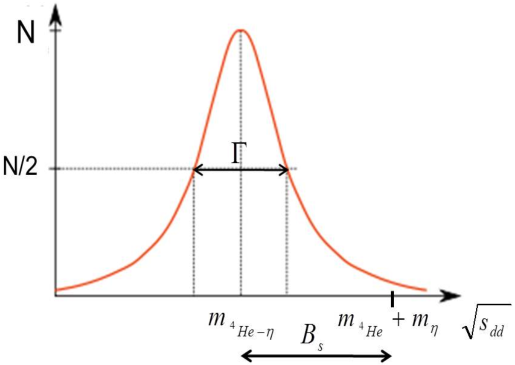


Excitation function

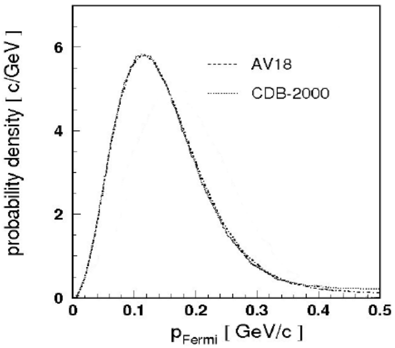
$({}^4\mathrm{He}\text{-}\eta)_{bs}$ **existence manifested by resonant-like structure below η production threshold**

MC Simulations - assumptions

Breit-Wigner distribution



Spectator Model



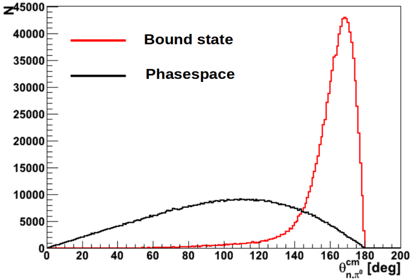
$$N\left(\sqrt{s_{dd}}\right) = \frac{1}{2\pi}\frac{\Gamma}{\left(\sqrt{s_{dd}} - m_{bs}\right)^2 + \Gamma^2/4}$$

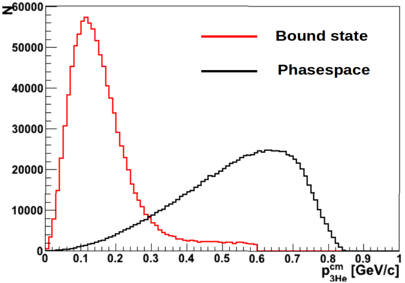
$$m_{^4He-\eta} = m_{^4He} + m_\eta - B_s$$

Kinematic mechanism of the reaction

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

- relative N-π angle in the CM: $\theta_{cm}^{N,\pi} \sim 180^\circ$
- low ^{3}He momentum in the CM



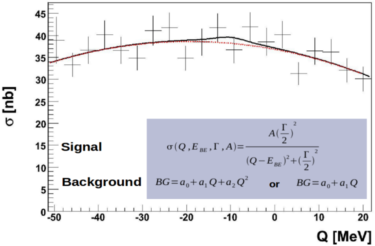


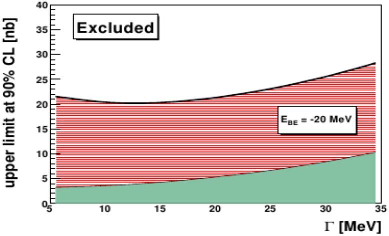
Experiment-May 2008

Channel: $dd \to (^4\text{He-}\eta)_{bs} \to {}^3\text{He}p\pi^-$ (norm: $dd \to {}^3\text{He}n$)

Measurement: performed with the beam momentum ramped from **2.185GeV/c to 2.400GeV/c**, corresponding to the range of excess energy **Q∈(-51,22)MeV**

Luminosity: $L=118\frac{1}{nb}$
Acceptance: A=53%





P. Adlarson et al., Phys. Rev. C87 (2013), 035204; W. Krzemien, PhD

Experiment-Nov/Dec 2010

Beamtime: Nov 26 - Dec 13, 2010

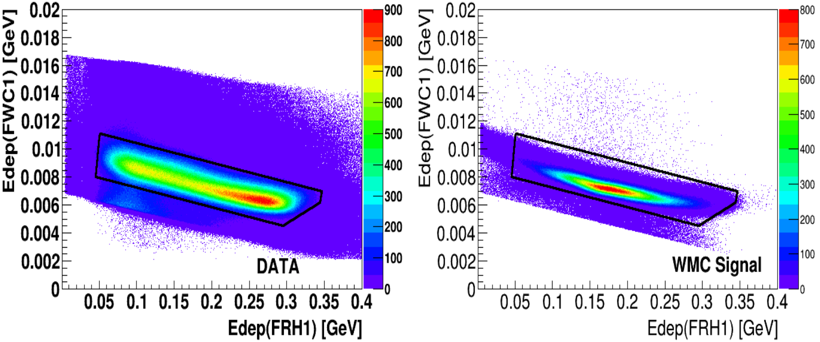
Channels: $dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^-$
$dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$

Measurement: performed with the beam momentum ramped from **2.127GeV/c to 2.422GeV/c**, corresponding to the range of excess energy **Q∈(-70,30)MeV**
Acceptance: A=53%
Luminosity: L≈1100$\frac{1}{nb}$ ($dd \rightarrow {}^3\text{He}n$ and $dd \rightarrow ppn_{sp}n_{sp}$)

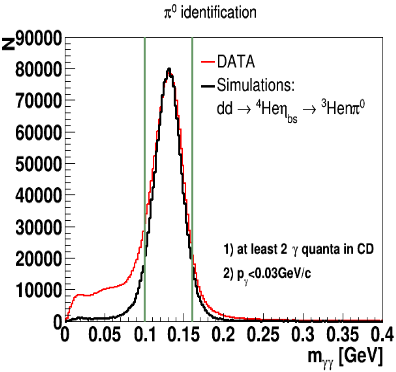
⇓

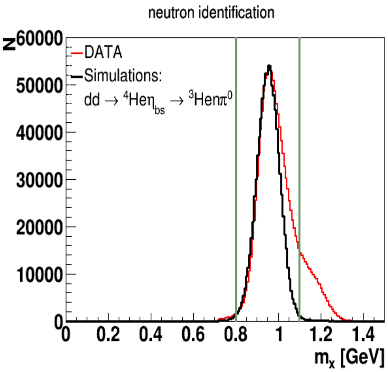
More than **10 times higher** statistics and two reactions were collected than in 2008 experiment.

^{3}He identification in Forward Detector



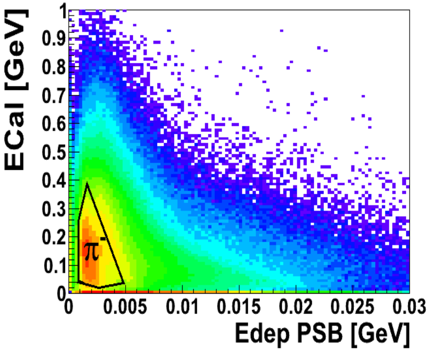
π^0 and neutron identification in Central Detector
$dd \rightarrow {}^3\mathrm{He} n \pi^0$

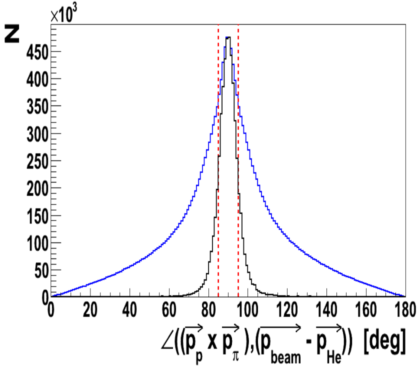




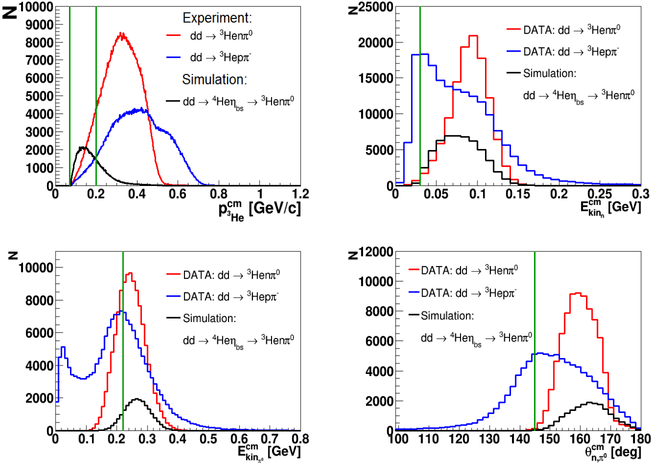
π^- and proton identification in Central Detector

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





Kinematic conditions
PRELIMINARY

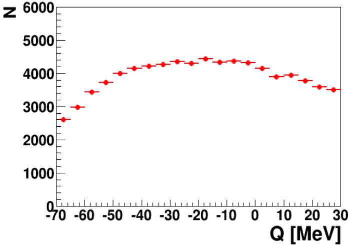


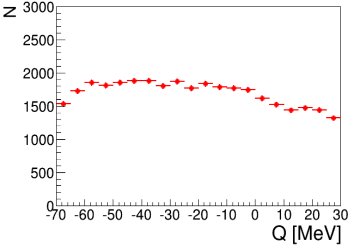
DATA: $dd \rightarrow {}^3\mathrm{He}p\pi^-$
DATA: $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$

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

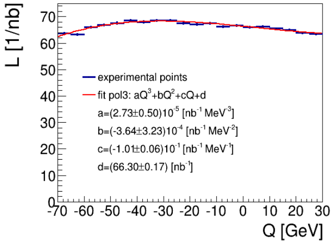
$dd \rightarrow {}^3\text{He}n\pi^0$ $dd \rightarrow {}^3\text{He}p\pi^-$

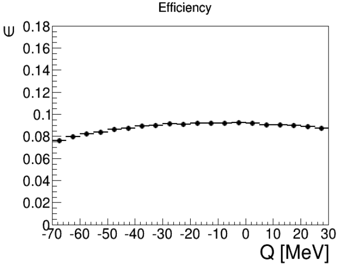
PRELIMINARY

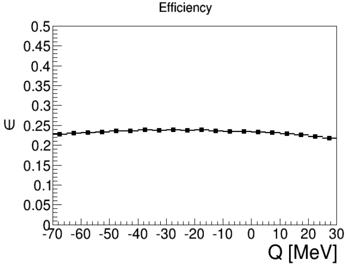




Luminosity: $dd \rightarrow ppn_{sp}n_{sp}$

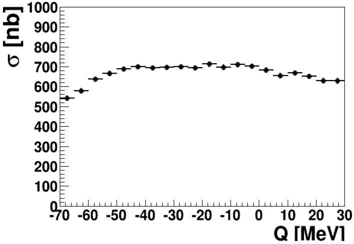


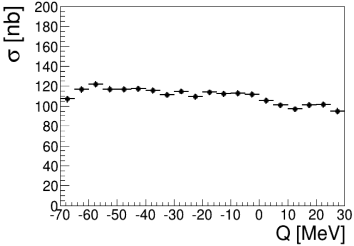


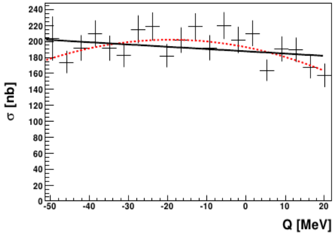


$dd \to {}^3\mathrm{He} n \pi^0$ $dd \to {}^3\mathrm{He} p \pi^-$

PRELIMINARY





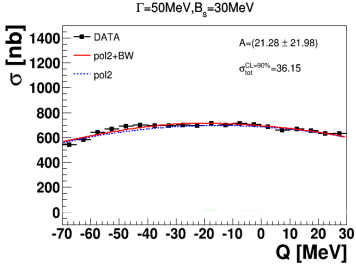


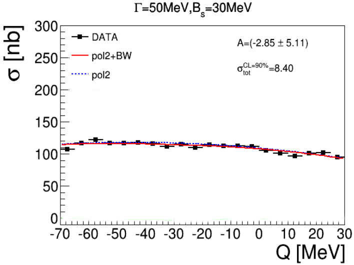
P. Adlarson et al., Phys. Rev. C87 (2013) 035204

Upper limit of the total cross section at CL=90%

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

PRELIMINARY



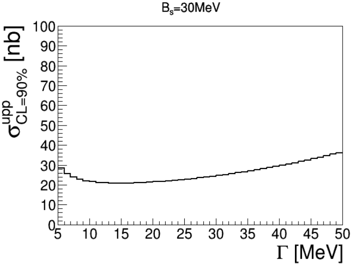


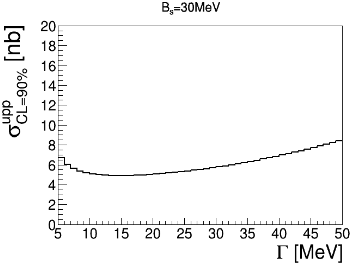
$$\sigma(Q,\Gamma,B_s,A) = \frac{A\cdot\Gamma^2/4}{(Q-B_s)^2+\Gamma^2/4}$$

Upper limit of the total cross section at CL=90%

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

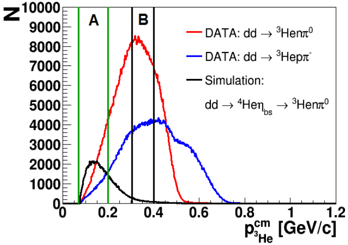
PRELIMINARY

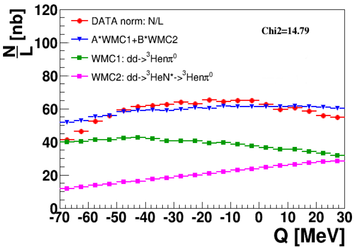


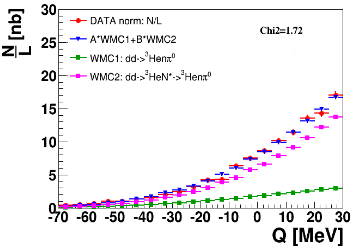


few nb!

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







Summary and Conclusions

- Exclusive measurement of the $dd \rightarrow {}^3\text{He}p\pi^-$ and $dd \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$ reactions 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)
- Preliminary result from 2010 measurement doesn't show a narrow signal of η-mesic nuclei
- The upper limit of the total cross section in order of **few nb**!
- New data set in ^{3}He-η system - Experiment in May 2014

Thank you for attention

INNOVACYJNA GOSPODARKA
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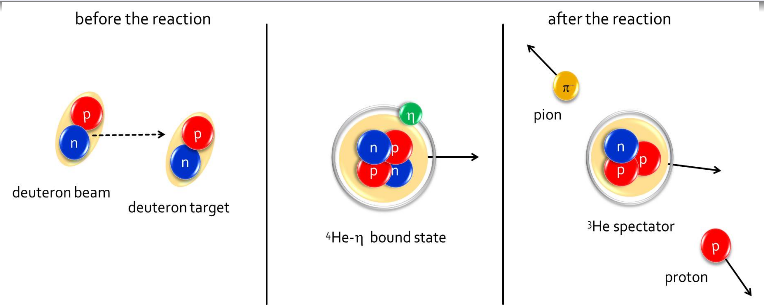
Kinematic mechanism of the reaction

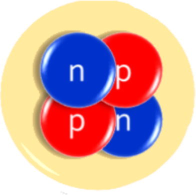
$$dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^-$$

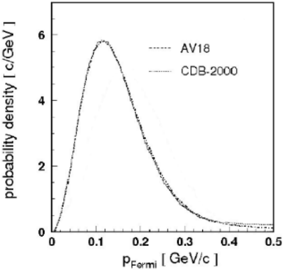


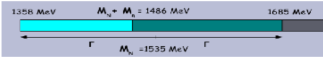
$$N^*:\ \vec{p}_n^{\,*} = \vec{p}_F^{\,*} \Rightarrow m_N^* = \left(s_{dd} + m_{^3He}^2 - 2\sqrt{s_{dd}}\sqrt{m_{^3He}^2 + |\vec{p}_F^{\,*}|^2}\right)^{\frac{1}{2}} \Rightarrow$$

$$|\vec{p}_{p,\pi^-}^{\,**}| = \frac{\lambda(m_{N*}^2, m_{\pi^-}^2, m_p^2)}{2m_{N*}}$$

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







How to estimate momentum distribution of N^* in the η-mesic helium?

Properties of nucleons and N^* resonance:

nucleon: $m_p \approx 938.3 MeV$ and $m_n \approx 939.6 MeV$ $J^P = \frac{1}{2}^+$

N^* resonance: $m_N^* \approx 1535 MeV$ $\Gamma \approx 150 MeV$ $J^P = \frac{1}{2}^-$

Main decay channels:

$N^* \rightarrow \pi N$ (35-55 %)

$N^* \rightarrow \eta N$ (30-55 %)

$N^* \rightarrow \pi\pi N$ (1-10 %)

New experiment-May/June 2014

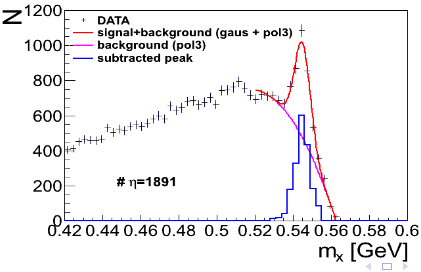
Channels: 1) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow ppp\pi^-$
2) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow ppn\pi^0$ 3) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow dp\pi^0$

Orbiting η

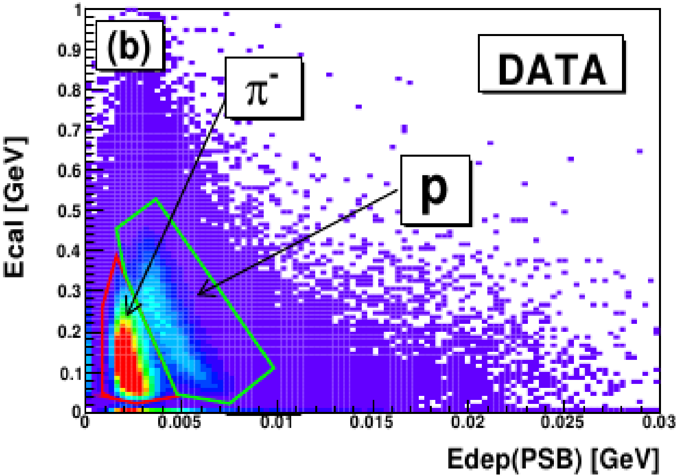
4) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}\ 2\gamma$ 5) $pd \rightarrow (^3\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}\ 6\gamma$

Measurement: p_{beam} : 1.468-1.615GeV/c, **Q∈(-50,20)MeV**

Luminosity: $L \approx 5000 \frac{1}{nb}$ $(pd \rightarrow {}^3\text{He-}\eta)$



test plot


(b)
DATA
π^-
p
Ecal [GeV]
Edep(PSB) [GeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.005
0.01
0.015
0.02
0.025
0.03

1. The deuteron beam momentum value p_{beam} is generated with uniform probability density distribution in range of $p_{beam} \in(2.127,2.422)$ GeV/c and then the square of invariant mass of the whole system s_{dd} is calculated using Eq. (5.2) presented in Sec. 5.2 while describing the simulation of main reaction considered in this thesis.

2. The square root $\sigma(\sqrt{s_{dd}})$ is distributed randomly according to the distribution presented as follows:

$$\sigma(\sqrt{s_{dd}}) = \int_{W_{min}}^{W_{max}} PS(W) \cdot BW\left(\sqrt{s_{dd}} - W - m_{^3He}, \Gamma_{N^*}, E_{N^*}\right) \cdot dW, \quad \text{(D.1)}$$

where:

- $W = \sqrt{s_{dd}} - m_{N^*} - m_{^3He}$

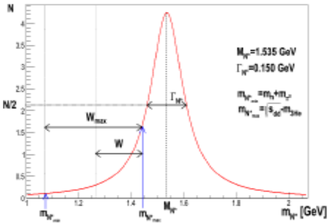
is the excess energy avaliable in the CM frame with minimum and maximum values equal to $W_{min} = 0$ and $W_{max} = \sqrt{s_{dd}} - m_{\pi^0} - m_n - m_{^3He}$,

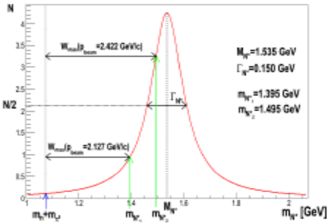
- $PS(W) = \sqrt{W}\left[\sqrt{s_{dd}} + m_{N^*} + m_{3He}\right]^{1/2}\left[s_{dd} - (m_{N^*} - m_{3He})^2\right]^{1/2} / \left(2\sqrt{s_{dd}}^3\right)$
$= \sqrt{W}\left[2\sqrt{s_{dd}} - W\right]^{1/2}\left[s_{dd} - (\sqrt{s_{dd}} - W - 2m_{3He})^2\right]^{1/2} / \left(2\sqrt{s_{dd}}^3\right)$

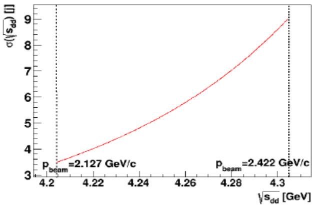
is a Phase Space factor for 2-body reactions which is proportional to $\sqrt{W}$ near the η production threshold and to 1/W above the threshold [58],

- $BW\left(\sqrt{s_{dd}} - W - m_{3He}, \Gamma_{N^*}, E_{N^*}\right) = \frac{\Gamma^2_{N^*}/4}{(m_{N^*}-E_{N^*})^2+\Gamma^2_{N^*}/4} = \frac{\Gamma^2_{N^*}/4}{(\sqrt{s_{dd}}-W-m_{3He}-E_{N^*})^2+\Gamma^2_{N^*}/4}$

is a Breit Wigner distribution of N^* resonance with energy E_{N^*}=1535 MeV and width Γ_{N^*}=150 MeV. The BW distribution is presented schematically in Fig. D.1 while $\sigma(\sqrt{s_{dd}})$ distribution in Fig. D.2.



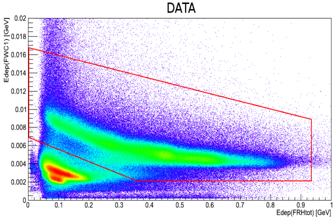




3. Excess energy available in the CM frame W is distributed according to the $PS(W) \cdot BW\left(\sqrt{s_{dd}} - W - m_{^3He}, \Gamma_{N^*}, E_{N^*}\right)$ distribution.
4. The resonance mass m_{N^*} is calculated as $m_{N^*} = \sqrt{s_{dd}} - W - m_{^3He}$ and is limited, because of two conditions:
   - $m_{N^*} + m_{^3He} \leq \sqrt{s_{dd}}$ (the whole avaliable energy is used to produce N^* and ^3He),
   - $m_{N^*} \geq m_{\pi^0} + m_n$ (resonance mass should be enough to decay into neutron and π^0).
5. The neutron and pion momentum vectors are simulated isotropically in the N^* frame in spherical coordinates and transformed into Cartesian coordinates. The absolute value of neutron and pion momenta $\vec{p}^{\,**}_{n,\pi^0}$ is fixed by equation (5.5) described in Sec. 5.2.
6. The gamma quanta are simulated isotropically in the π^0 frame in spherical coordinates with momenta $\vec{p}^{\,***}_{\gamma} = m_{\pi^0}/2$.
7. The four momentum vectors of ^{3}He, neutron and gamma quanta are transformed into the center of mass frame and next into laboratory frame

Preselection

1 charged in FD && (cuts for ^{3}He stopped in FRH)



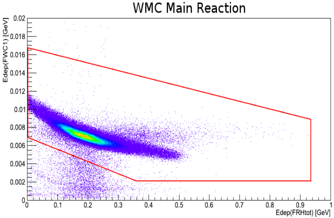
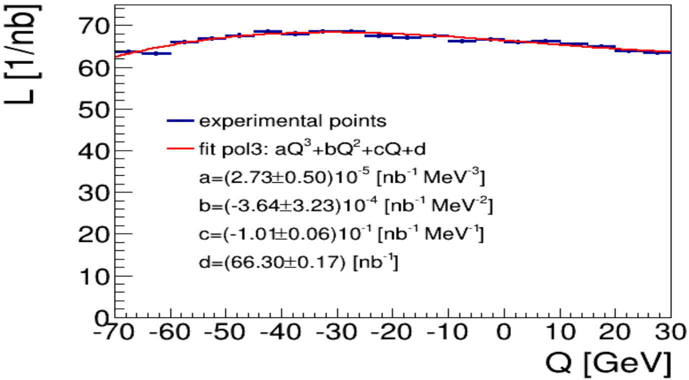


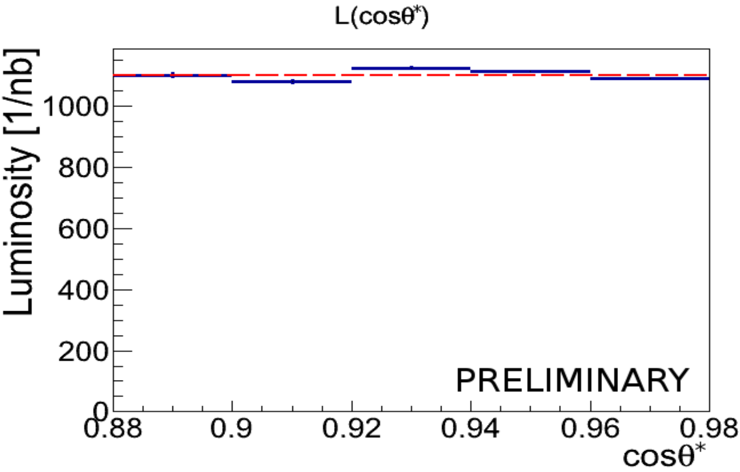
Figure: Cuts in Edep(FWC1)vsEdep(FRH1$_{tot}$).

total luminosity



$$L_{tot}=(1329\pm2)nb^{-1}$$

$$\mathrm{L}=(1329\pm2_{stat}\pm108_{syst}\pm64_{norm})nb^{-1}$$



$$L_{av} = (1102 \pm 2) nb^{-1}$$

$$L = (1102 \pm 2_{stat} \pm 28_{syst} \pm 107_{norm}) nb^{-1}$$