Search for the He-$\eta$ bound state with the WASA-at-COSY facility

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Outline

1. Eta-mesic bound states with a light nuclei
2. Search for $\eta$-mesic nuclei with WASA-at-COSY
3. Experiment
4. Summary and perspectives
Eta-mesic bound states with a light nuclei
Search for $\eta$-mesic nuclei with WASA-at-COSY Experiment
Summary and perspectives

$\eta$-mesic bound state

Atomic nucleus

\[ m = Z \cdot m_p + N \cdot m_n - B_s \]

\[ B_s = \Delta mc^2 \]

$\eta$-mesic nucleus

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

\[ m_{bs} = m_{^4\text{He}} + m_\eta - B_s \]
\(\eta\)-mesic bound state

Conditions for the existence of \(\eta\)-mesic nuclei

\[ \text{Re} a_{\eta\text{-nucleus}} < 0 \]
\[ \left| \text{Re} a_{\eta\text{-nucleus}} \right| > \left| \text{Im} a_{\eta\text{-nucleus}} \right| \]

**Attractive interaction between \(\eta\) and \(N\)**

\[ \downarrow \]

**Possible existence of \(\eta\)-mesic bound state for \(A > 12\)**
Recent theoretical investigations of hadronic- and photoproduction of $\eta$ meson

\[
0.27 \, \text{fm} \leq \text{Re} a_{\eta N} \leq 1.05 \, \text{fm} \\
0.19 \, \text{fm} \leq \text{Im} a_{\eta N} \leq 0.39 \, \text{fm}
\]


$\Gamma \in (7, 40) \text{MeV}$
$B_s \in (5, 15) \text{MeV}$

$^4\text{He}-\eta$ _bs_  \hspace{1cm} (T-$\eta$) _bs_

$^3\text{He}-\eta$ _bs_  \hspace{1cm} (d-$\eta$) _bs_

$\Gamma_{^4\text{He}} = 11.47 \text{MeV}$
$B_{^4\text{He}} = 6.30 \text{MeV}$

No $^3\text{He}$-eta bound state exists


$^3\text{He}$-eta bound state exists

$\Gamma_{^3\text{He}} = 11.47 \text{MeV}$
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Production of $^4\text{He}-\eta$ in dd collision

\[ dd \rightarrow \left( ^4\text{He}-\eta \right)_{bs} \rightarrow ^3\text{He} \ p \ \pi^- \]
\[ dd \rightarrow \left( ^4\text{He}-\eta \right)_{bs} \rightarrow ^3\text{He} \ n \ \pi^0 \rightarrow ^3\text{He} \ n \ \gamma \ \gamma \]
\[ dd \rightarrow \left( ^4\text{He}-\eta \right)_{bs} \rightarrow d \ p \ p \ \pi^- \]
\[ dd \rightarrow \left( ^4\text{He}-\eta \right)_{bs} \rightarrow T \ p \ \pi^0 \rightarrow T \ p \ \gamma \ \gamma \]
Kinematical mechanism of the reaction

\[ dd \rightarrow (^{4}\text{He}-\eta)_{bs} \rightarrow ^{3}\text{He}p\pi^- \]
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Angular distributions of outgoing particles

\[ dd \rightarrow (^4\text{He}-\eta)_{bs} \rightarrow ^3\text{He}p\pi^- \]
Angular distributions of outgoing particles

\[ dd \rightarrow ({}^4\text{He}-\eta)_{bs} \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma \]
Figure 2.1: Geometrical acceptances of the WASA-at-COSY detector for the $dd \rightarrow (^4\text{He}-\eta)_{bs} \rightarrow ^3\text{He} p \pi^-$ (left) and $dd \rightarrow (^4\text{He}-\eta)_{bs} \rightarrow ^3\text{He} n \pi^0 \rightarrow ^3\text{He} n \gamma \gamma$ reaction (right). Acceptance is calculated for three different bound state width values and AV18 potential model describing nucleon momentum distribution inside $^4\text{He}$. 
Simulation-assumptions

- Resonant structure of the eta-mesic bound state given by Breit-Wigner distribution (with assumed width and binding energy)
- Nucleon momenta in atomic nuclei described by Fermi distributions
- Spectator model
Expected results of the measurement

Angle between p and $\pi^-$ in the CM frame $\Theta_{CMN^*} = 180^0$

Excitation function

$(^4\text{He}-\eta)_{bs}$ existence manifested by resonant-like structure below $\eta$ production threshold
Exp. No. 186.1: Search for the $\eta$-He bound state with WASA-at-COSY

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

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

Time: $T=16.5h$
Acceptance: $A=53\%$
Luminosity: $L=3 \cdot 10^{30} cm^{-2} s^{-1}$

$\downarrow$

Upper limit of the total cross section: $\sigma=20 nb$
Exp. No. 186.2: Search for the $\eta$-He bound state with WASA-at-COSY

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 $2.127\text{GeV}/c$ to $2.422\text{GeV}/c$, corresponding to the range of excess energy $Q \in (-70,30)\text{MeV}$
Experiment-Nov/Dec 2010

Time: $T=154\, h$
Acceptance: $A=53\%$
Luminosity: $L=8.2 \cdot 10^{30} \, cm^{-2} s^{-1}$

Taking into account the fact that there were two reactions measured, in total more than 40 times higher statistics were collected than in experiment carried out in 2008.
Summary and perspectives

Chance for the discovery of the \((^4\text{He}-\eta)_{bs}\) with the WASA-at-COSY facility (study of the excitation function)

\[ \downarrow \]

- Determination of the bound state **width** and **binding energy** of \((^4\text{He}-\eta)_{bs}\)

- Investigation of interaction of the \(\eta\) meson and the nucleons inside a nuclear matter

- Information about resonances in nuclear matter \((N^*(1535))\)

- Information about \(\eta\) meson structure (wave function)

If no peak observed \(\Rightarrow\) determination of the **upper limit of the total cross section** with accuracy of few nb.
Thank you for attention