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Search for the ^{4}He $-\eta$ bound state with WASA-at-COSY

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We conduct a search for the $^4\mathrm{He}-\eta$ bound state with WASA-at-COSY facility, via a measurement of the excitation functions for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction, where the outgoing $p-\pi^-$ pairs originate from the conversion of the η meson on a nucleon inside the He nucleus. In June, 2008 first measurements of the excitation functions for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction were performed. In the experiment we used a slowly ramped COSY deuteron beam, scanning the range of momenta corresponding to the variation of the excess energy for the $^4He-\eta$ system from -51.4 MeV to 22 MeV.

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1. Introduction

The investigation of the exotic objects in the nuclear physics is a proven method for revealing many interesting properties of nuclear systems and for accessing to an unexplored areas of physics. The recent progress in the spectroscopy of deeply bound pionic atoms has permitted to obtain deeper insights into the meson-nucleus interaction and the in-medium behaviour of spontaneous chiral symmetry breaking [1].

It is also conceivable that neutral mesons such as $\eta, \bar{K}, \omega, \eta'$ can form bound states with atomic nuclei. In this case the binding is exclusively due to the strong interaction and the bound state - *mesic nucleus* - can be considered as a meson moving in the mean field of the nucleons in the nucleus. Due to the strong attractive η-nucleon interaction [2], the η-mesic nuclei are ones of the most promising candidates for such states.

The discovery of the η-mesic nuclei would be interesting on its own but it would be also valuable for investigations of the $\eta-N$ interaction and for the study of the in-medium properties of the N^* resonance [3] and of the η meson [4]. It could also help to determine the flavor singlet component of the η wave function [5].

The existence of η-mesic nuclei was postulated in 1986 by Haider and Liu [6], and since then a search for such states was conducted in many experiments in the past [7, 8, 9, 10, 11, 12] and is being continued at COSY [13, 14, 15, 16], JINR [9], J-PARC [17] and MAMI [12]. However, up to now no firm experimental evidence for η-mesic nuclei was found.

A very strong final state interaction (FSI) observed in the $dd \rightarrow {}^4\mathrm{He}\eta$ reaction close to kinematical threshold and interpreted as possible indication of ${}^4\mathrm{He}-\eta$ bound state [18] suggests, that ${}^4\mathrm{He}-\eta$ system is a good candidate for experimental study of possible binding.

Taking into account the above arguments, we performed a search for η-mesic ^{4}He by measuring the excitation function for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction in the vicinity of the η production threshold.

2. Method

In our experimental studies, we used the deuteron-deuteron collisions at energies around the η production threshold for production of the $\eta-{}^4\mathrm{He}$ bound state. We expect, that the decay of such state proceeds via absorption of the η meson on one of the nucleons in the ^{4}He nucleus leading to excitation of the $N^\star(1535)$ resonance which subsequently decays in pion-nucleon pair. The remaining three nucleons play a role of spectators and they are likely to bind forming ^{3}He or ^{3}H nucleus. This scenario is schematically presented in Fig. 1.

According to the discussed scheme, there exist four equivalent decay channels of the $({}^4\mathrm{He}-\eta)_{bound}$ state:

- $({}^4\mathrm{He}-\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$
- $({}^4\mathrm{He}-\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0$
- $({}^4\mathrm{He}-\eta)_{bound} \rightarrow {}^3\mathrm{H}p\pi^0$
- $({}^4\mathrm{He}-\eta)_{bound} \rightarrow {}^3\mathrm{H}n\pi^+$

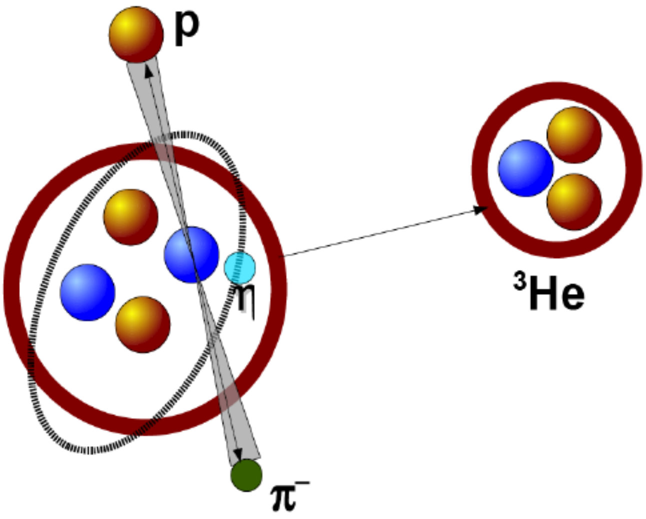

Figure 1: Schematic picture of the $(^4\mathrm{He}-\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ decay. In the first step the η meson is absorbed on one of the neutrons and the $N^\star$ resonance is formed. Next, the N* decays into a $p-\pi^-$ pair. The ^{3}He plays the role of a spectator.

In our experiment we concentrated on the $^3\mathrm{He}p\pi^-$ decay mode due to the highest acceptance of the WASA-at-COSY detector in this case. The outgoing ^{3}He nucleus plays the role of a spectator and, therefore, we expect that its momentum in the CM frame is relatively low and can be described by the Fermi momentum distribution of nucleons in the ^{4}He nucleus. This signature allows to suppress background from reactions leading to the $^3\mathrm{He}p\pi^-$ final state but proceeding without formation of the intermediate $(^4\mathrm{He}-\eta)_{bound}$ state and, therefore, resulting on the average in much higher CM momenta of ^{3}He (see Fig. 2).

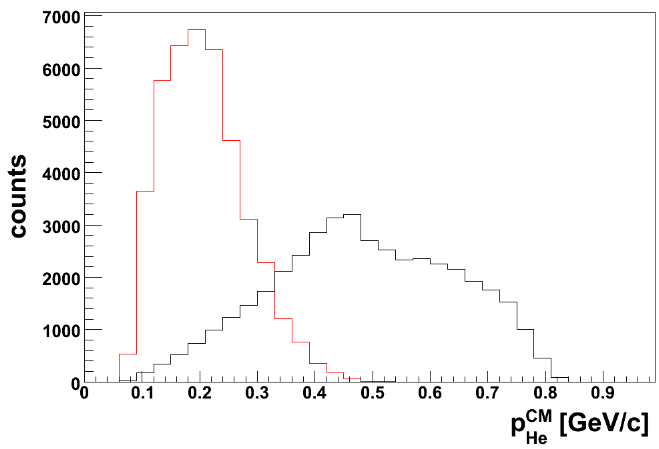

Figure 2: Distribution of the ^{3}He momentum in the CM system obtained in simulation of the processes leading to the creation of the $^4\mathrm{He}\eta$ bound state: $dd \rightarrow (^4\mathrm{He}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ (red line) and of the direct $dd \rightarrow {}^3\mathrm{He}p\pi^-$ decay (black line).

A kinematic variable correlated with the ^{3}He CM momentum is the relative angle of the outgoing $p-\pi^-$ pair. In the limit of ^{3}He produced at rest in the CM frame this angle is exactly equal to 180° but due to the presence of the Fermi motion it is smeared by about 30°(see Fig. 3).

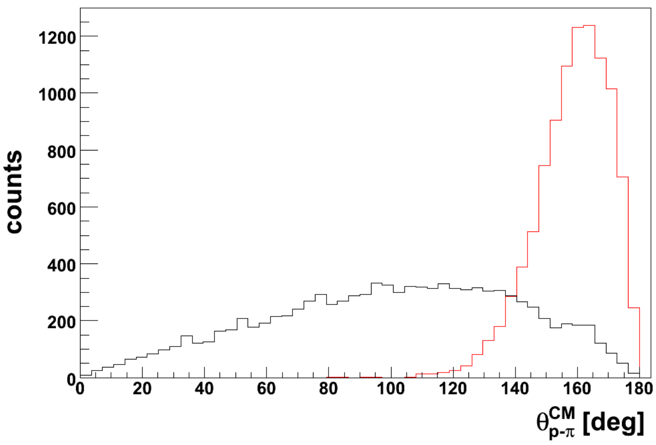

Figure 3: Distribution of the $p-\pi^-$ opening angle in the CM system obtained in simulation of the processes leading to the creation of the ^{4}Heη bound state: $dd \to (^4\text{He}\eta)_{bound} \to {}^3\text{He}p\pi^-$ (red line) and of the direct $dd \to {}^3\text{He}p\pi^-$ reaction (black line).

The principle of the present experiment was based on the measurement of the excitation function of the $dd \to {}^3\text{He}p\pi^-$ reaction for energies in the vicinity of the η production threshold and on the selection of events with low ^{3}He CM momenta. In the case of existence of the $^4\text{He}-\eta$ bound state we expected to observe a resonance-like structure in the excitation function at the reaction CM energies below the η threshold. From the central energy of the observed structure E^{CM} one can determine the binding energy of the $(^4\text{He}-\eta)$ system:

$$E_{BE} = m_{He} + m_\eta - E^{CM}. \tag{2.1}$$

The width of the structure is equal to the width of the bound state.

3. Experiment

In June 2008 we performed a search for the η-mesic ^{4}He by measuring the excitation function of the $dd \to^3$ He$p\pi^-$ reaction near the η meson production threshold using the WASA-at-COSY detector [19]. During the experimental run the momentum of the deuteron beam was varied continuously within each acceleration cycle from 2.185 GeV/c to 2.400 GeV/c, crossing the kinematic threshold for the η production in the $dd \to {}^4\text{He}\,\eta$ reaction at 2.336 GeV/c. This range of beam momenta corresponds to the variation of $^4\text{He}-\eta$ excess energy from -51.4 MeV to 22 MeV.

The identification of the ^{3}He was conducted using the $\Delta E - \Delta E$ techniques comparing the energy losses in two layers of the Forward Range Hodoscope. The energy loss in the Plastic Scintillator Barrel was combined with the energy deposited in the Electromagnetic Calorimeter to identify protons and pions.

We constructed two types of excitation function for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction. They differ in the selection of the events and in the way of normalizing the data points. The first excitation function uses events from the "signal-rich" region corresponding to the ^{3}He CM momenta below 0.3 GeV/c. The counts are plotted as a function of the beam momentum as it is shown Fig. 4(top). The obtained function is smooth an no clear signal, which could be interpreted as a resonance-like structure, is visible. A similar dependence was obtained for events originating from the "signal-poor" region corresponding to ^{3}He CM momenta above 0.3 GeV/c (see Fig. 4(middle)). We checked also for possible structures in the difference between the discussed functions for the "signal-rich" and "signal-poor" region. We multiplied the function for the "signal-poor" region by a factor chosen in such a way, that the difference of the two functions for the lowest beam momentum bin is equal to zero. This difference is presented in Fig. 4(bottom). The obtained dependence is flat and is consistent with zero. No resonance structure is visible.

However, we do not treat this result as a final conclusion of non observation of the $^3\mathrm{He}-\eta$ bound state, since one can apply further cuts to reduce the background. Additional cuts on the p and π^- kinetic energy distributions and the $p-\pi^-$ opening angle in the CM system lead us to the construction of a second excitation curve. The CM kinetic energies of protons and pions originate from the mass deficit $m_\eta - m_\pi$ are around 50 MeV and 350 MeV, respectively. We selected the kinetic energy of protons smaller than 200 MeV and of pions from the interval (180, 400) MeV. We applied also a cut on the relative $p-\pi^-$ angle in the CM system in the range of (140°-180°). The number of selected events in each beam momentum interval was divided by the corresponding integrated luminosity. This result is shown in Fig. 5.

The integrated luminosity in the experiment was determined using the $dd \rightarrow {}^3\mathrm{He}n$ reaction and it equals 117.9 $\pm$13.6 nb^{-1} [20]. The relative normalization of points of the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ excitation function was based on the quasi-elastic proton-proton scattering.

In order to use the Breit-Wigner distribution for the description of a possible resonance structure in the excitation function, we translated the beam momentum intervals into intervals of the excess energy with respect to the $^4\mathrm{He}\eta$ production threshold. The excitation function presented in Fig. 5 can be well described by a second order polynomial resulting in the chi-squared value per degree of freedom of 0.98. In the excitation function we observe no structure which could be interpreted as a resonance originating from decay of the η-mesic ^{4}He.

We assumed, that a signal from the bound state in the excitation curve determined as a function of the excess energy Q with respect to the $^4\mathrm{He}-\eta$ threshold, can be described by the Breit-Wigner shape:

$$\sigma(Q, E_{BE}, \Gamma, A) = \frac{A \cdot (\frac{\Gamma}{2})^2}{(Q-E_{BE})^2 + (\frac{\Gamma}{2})^2}, \tag{3.1}$$

where E_{BE} is the binding energy, Γ is the width and A is the amplitude. The value of the Breit-Wigner function for the central energy ($Q = E_{BE}$) corresponds to the maximum cross-section for the decay of the η-mesic ^{4}He into the $^3\mathrm{He}p\pi^-$ channel. In order to determine an upper limit for the cross-section for formation of the $^4\mathrm{He}-\eta$ bound state and its decay into the $^3\mathrm{He}p\pi^-$ channel we fitted the excitation function with quadratic function describing the background combined with the Breit-Wigner function. In the fit we adjusted the quadratic background and the amplitude A of the Breit-Wigner distribution. The binding energy E_{BE} and the width Γ were fixed during the fit.

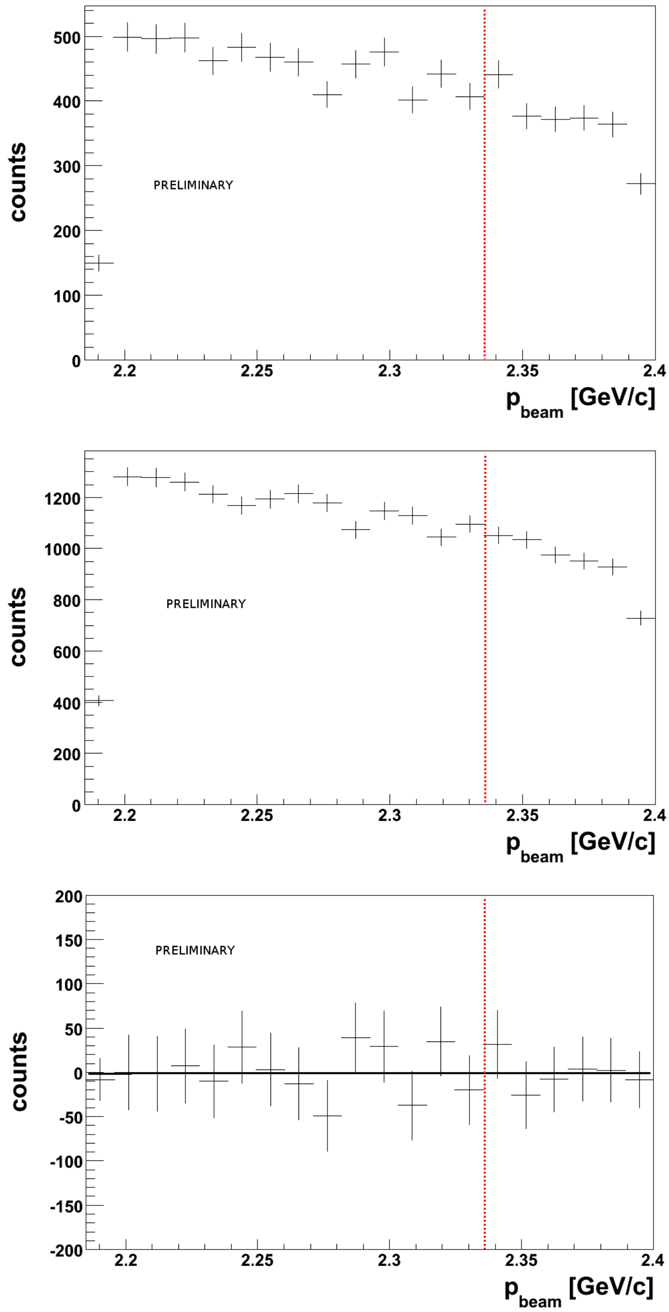

Figure 4: Excitation function for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction for the "signal-rich" region corresponding to ^{3}He momentum below 0.3 GeV/c (upper panel) and the "signal-poor" region with ^{3}He momentum above 0.3 GeV/c (middle panel). Difference of the excitation functions for the "signal-rich" and "signal-poor" regions after the normalization to the lowest beam momentum bin is shown in the lower panel. The black solid line represents a straight line fit. The beam momentum corresponding to the $^4\mathrm{He} - \eta$ threshold is marked by the vertical red line.

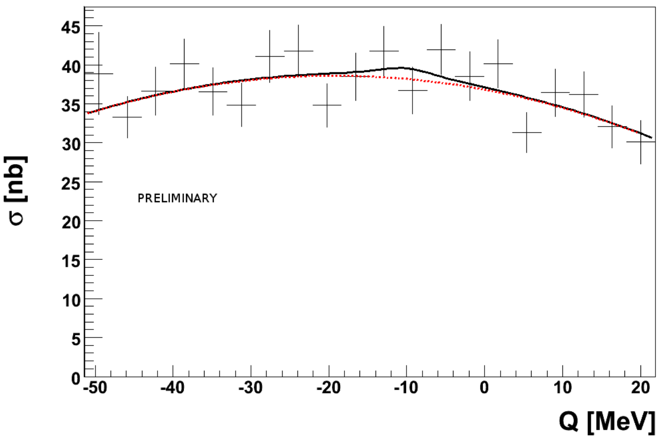

Figure 5: Excitation function for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction obtained by normalizing the events selected in individual excess energy intervals by the corresponding integrated luminosities. The solid line represents a fit with second order polynomial combined with a Breit-Wigner function with fixed binding energy and width equal to -10 and 10 MeV, respectively. The dotted line corresponds to the contribution from the second order polynomial in the performed fit. The σ values are not corrected for acceptance and efficiency cuts.

An example of the fit with E_{BE}=-10 MeV and Γ=10 MeV is shown in Fig. 5. The fit was performed for various values of the binding energy and the width representing different hypothesis of the bound state properties. In each case, the value of the amplitude A is consistent with zero within the uncertainty σ_A, which confirms the hypothesis of non-observation of the signal.

In order to calculate an upper limit for the $dd \rightarrow ({}^4\mathrm{He}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ cross-section, the σ_A values obtained in the above described fit had to be corrected for the efficiency ε (equal to 19%) and multiplied by the statistical factor k equal to 1.64485 corresponding to the probability confidence level of 90%:

We obtained the preliminary upper limits for the cross-sections of 28, 32 and 41 nb for production and decays of the bound state with a width of 10, 20 and 30 MeV, respectively.

4. Outlook

In November 2010 a new two-week measurement was performed with WASA-at-COSY. We collected data with approximately 20 times higher statistics. In addition to the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ channel we registered also the $dd \rightarrow {}^3\mathrm{He}n\pi^0$ reaction. The data analysis is undergoing. After two weeks of measurement with an estimated luminosity of $4 \cdot 10^{30}$ cm^{-2} s^{-1}, we expect a statistical sensitivity of a few nb (σ). A non-observation of this signal will significantly lower the upper limit for the existence of the bound state.

5. Support

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References

[1] S. Hirenzaki, *Prog. Theor. Phys. Suppl.* **168**, 458-465 (2007).

[2] A. M. Green, S. Wycech, *Phys. Rev.* **C71**, 014001 (2005).

[3] D. Jido, H. Nagahiro, S. Hirenzaki, *Phys. Rev.* **C66**, 045202 (2002).

[4] T. Inoue, E. Oset, *Nucl. Phys.* **A710**, 354 (2002).

[5] S. D. Bass, A. W. Thomas, *Acta. Phys. Pol. B* **41**, 2239 (2010) .

[6] Q. Haider, L.C. Liu, *Phys. Lett.* **B172**, 257 (1986).

[7] B. J. Lieb *et al.*, *Proc. Int. Nucl. Phys. Conf., Sao Paulo, Brazil* (1989).

[8] G. A. Sokol *et al.*, *arXiv:nucl-ex/9905006* (1999)

[9] M. Kh. Anikina *et al.*, *arXiv:nucl-ex/0412036* (2004).

[10] A. Gillitzer, *Acta Phys. Slovaca* **56**, 269 (2006).

[11] A. Budzanowski *et al.*, *Phys. Rev.* **C79**, 061001(R) (2009).

[12] B. Krusche, F. Pheron, Y. Magrbhi *Acta. Phys. Pol. B* **41**,2249 (2010).

[13] P. Moskal, J. Smyrski, *Acta. Phys. Pol. B* **41**, 2281 (2010).

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

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

[16] W. Krzemień *et al.*, *Int. J. Mod. Phys.* **A24**,576 (2009).

[17] H. Fujioka, K. Itahashi, *Acta. Phys. Pol. B* **41**, 2261 (2010).

[18] N. Willis *e*t al., *Phys.Lett.* **B406**, 14 (1997).

[19] W. Krzemień *et al.*, *Acta Phys.Polon.Supp.* **2**, 141-148 (2009).

[20] W. Krzemień, PhD thesis, Jagiellonian University, Poland (2011).