ANALYSIS OF THE $pd \to pd\pi^0$ REACTION MEASURED WITH WASA-at-COSY FACILITY IN ORDER TO SEARCH FOR η-MESIC HELIUM*

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In this report, we briefly present the preliminary results of the search for ^{3}He–η bound system in $pd \to pd\pi^0$ reaction.

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1. Introduction

The possibility of existence of a bound state consisting of a nucleus bound via the strong interaction with a neutral meson, such as η, η', K, ω, has excited nuclear physicists for over 30 years, from the moment it was for the first time postulated by Haider and Liu [1]. However, till now, the existence of the so-called *mesic nucleus* has not been experimentally confirmed. Recently, both theoretical [2–17] and experimental studies [18–31] are ongoing.

The most recent experiment dedicated to the search for η-mesic helium has been performed by the WASA-at-COSY Collaboration in Forschungszentrum Jülich (Germany). The measurements were carried out with high statistics and high acceptance with the WASA detection setup [32] in deuteron–deuteron (^{4}He–η) [23–26] and proton–deuteron (^{3}He–η) [26–31] fusion reactions.

In this report, status and perspectives of the search for the η-mesic helium nuclei via $pd \to pd\pi^0$ reaction are presented.

2. Analysis of the $pd \to pd\pi^0$ reaction

One of the hypothesis postulates that reaction of the η-mesic nucleus production and decay proceeds via scheme presented in Fig. 1.

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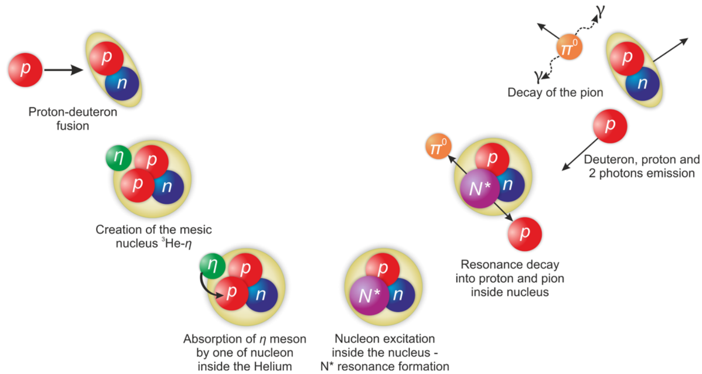

Fig. 1. Model of the bound state production and decay in the $pd \to pd\pi^0$ reaction.

The proton–deuteron collision leads to the formation of helium nucleus interacting with the η meson via strong interaction. Next, the meson might be absorbed by one of the nucleons inside ^{3}He leading to its excitation to N^* (1535) resonance. The resonance decays into the p–π^0 pair and, subsequently, π^0 decays into 2γ quanta. The deuteron plays a role of spectator.

The above kinematical model was applied in Monte Carlo simulations of the $pd \to (^3\text{He}–\eta)_{\text{bound}} \to pd\pi^0$ reaction. The simulation results were compared with experimental data in order to select kinematical region corresponding to the bound state production in the $pd \to pd\pi^0$ process.

Events selection started with particles identification. The measurement of energy loss in the thin plastic scintillator (PSB) combined with the energy deposited in the electromagnetic calorimeter (SEC) [32] was used to identify protons. The events corresponding to the charged pions registered in the detector were subtracted (see Fig. 2).

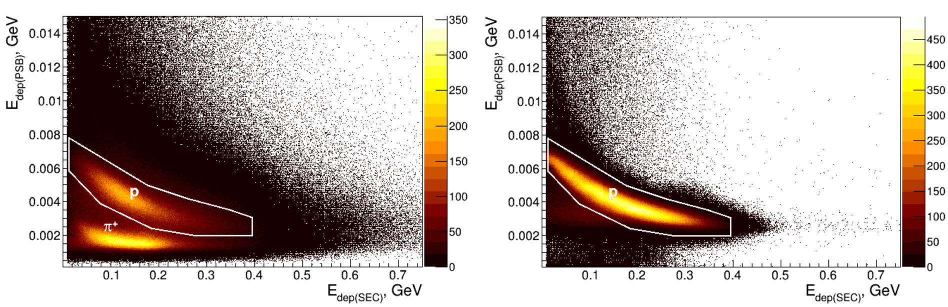

Fig. 2. Experimental (left panel) and simulated (right panel) spectra of the energy deposited in the SEC as a function of the energy loss in the PSB. The selected area for protons is marked with the white line.

The π^0 were reconstructed from the invariant mass of 2γ quanta originating from its decay. The cut applied in invariant mass spectrum, based on Monte Carlo simulations, is presented in the left panel of Fig. 3.

In order to select kinematical region corresponding to the bound state ^{3}He–η, we apply a cut on the opening angle between proton and π^0 in the center-of-mass frame $\theta^{\mathrm{cm}}_{\pi^0-p}$ corresponding to the region of (155°–180°) as expected on the basis of the simulations (see the right panel of Fig. 3).

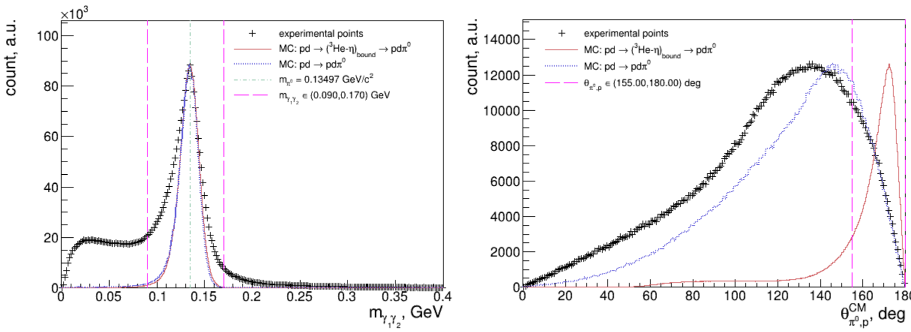

Fig. 3. Left panel: π^0 identification based on invariant mass spectrum of 2γ quanta. Right panel: π^0–p opening angle in the center-of-mass frame $\theta^{\mathrm{cm}}_{\pi^0-p}$. Black crosses represent experimental points. Solid and dotted lines show simulation of signal and background reactions, respectively. Vertical dashed lines indicate the applied selection cuts.

An additional cut, which was used to improve selection of events from the $pd \to (^3\mathrm{He}–\eta)_{\mathrm{bound}} \to pd\pi^0$ reaction, was applied in the deuteron scattering angle spectrum in the laboratory frame corresponding to the region of geometrical acceptance of the Forward Detector (3°–18°) as it is shown in the left panel of Fig. 4.

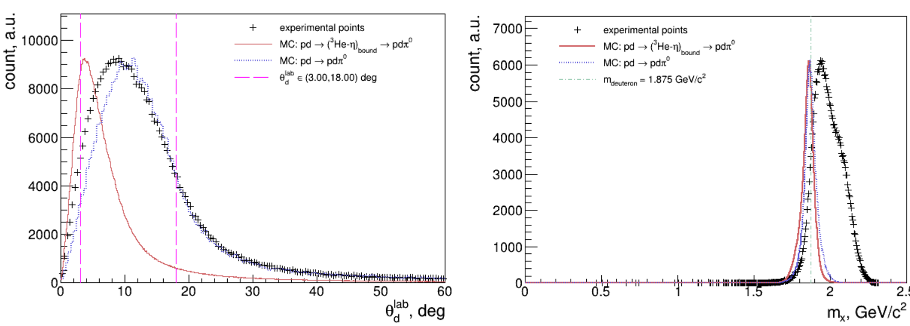

Fig. 4. Left panel: deuteron scatering angle in the laboratory frame. Black crosses represent experimental points. Solid and dotted lines show simulation of signal and background reactions, respectively. Vertical dashed lines indicate the applied selection cuts. Right panel: the missing mass spectrum for $pd \to pX\pi^0$ reaction.

Knowing four momenta of proton beam $(E_{\rm beam}, \vec{p}_{\rm beam})$, deuteron target $(E_{\rm targed} = m_{\rm deuteron}, \vec{p}_{\rm targed} = 0)$, outgoing proton $(E_p, \vec{p}_p)$ and gamma quanta $(E_{\gamma_1}, \vec{p}_{\gamma_1})$, $(E_{\gamma_2}, \vec{p}_{\gamma_2})$, and employing the principle of momentum and energy conservation, we calculated the missing mass according to formula (1)

$$m_x = \left[E_x^2 - (\vec{p}_x)^2\right]^{\frac{1}{2}} = \Big[(E_{\rm beam} + E_{\rm targed} - E_p - E_{\gamma_1} - E_{\gamma_2})^2 - (\vec{p}_{\rm beam} + \vec{p}_{\rm targed} - \vec{p}_p - \vec{p}_{\gamma_1} - \vec{p}_{\gamma_2})^2\Big]^{\frac{1}{2}} . \tag{1}$$

The missing mass spectrum is shown in the right panel of Fig. 4.

Monte Carlo simulations of the $pd \to (^3\text{He}\text{–}\eta)_{\rm bound} \to pd\pi^0$ process allows to determine *acceptance* and *efficiency* as a function of the excess energy. Obtained geometrical acceptance is equal to about 30%, while the full efficiency including all cuts applied in the analysis is equal to about 7% (see the left panel of Fig. 5).

In order to calculate the *integrated luminosity* for each excess energy interval, we used quasi-free $pd \to ppn_{\rm spectator}$ reaction [31]. Total integrated luminosity is equal to $L = (2295 \pm 3_{\rm stat} \pm 91_{\rm syst})$ nb^{-1} and is presented in the left panel of Fig. 5.

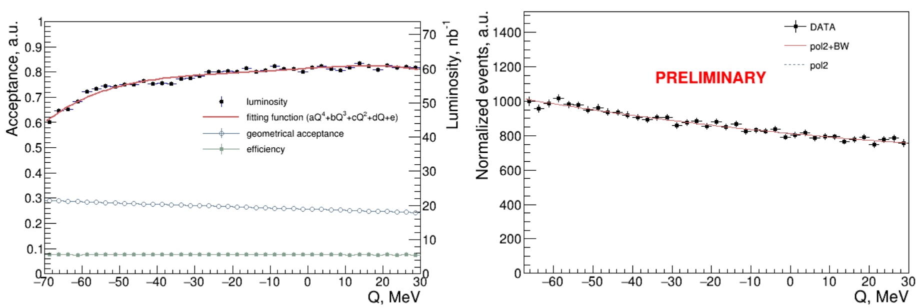

Fig. 5. Left panel: efficiency for the $pd \to pd\pi^0$ reaction as a function of excess energy Q and integrated luminosity calculated for the experimental data for the quasi-free $pd \to ppn_{\rm spectator}$ reaction. Right panel: excitation function for the $pd \to pd\pi^0$ process after applying selection criteria described in the text.

3. Preliminary results

Excitation function is obtained by normalizing the events selected in individual excess energy intervals by the integrated luminosity and efficiency. Example spectrum is presented in the right panel of Fig. 5. The preliminary excitation function does not show the structure which could be interpreted as a signal of the $(^3\text{He}\text{–}\eta)_{\rm bound}$ system.

In order to determine an *upper limit* of the total cross section for formation of the ^{3}He–η bound state and its decay in the $pd \to pd\pi^0$ channel, we performed the fit with second order polynomial describing background and the Breit–Wigner function which can account for the signal from the $(^3\text{He}–\eta)_\text{bound}$ system. The solid line in the right panel of Fig. 5 shows a fit with a sum of second order polynomial and a Breit–Wigner function. Binding energy B_s and width Γ are fixed and equal to -30 MeV and 40 MeV, respectively.

The fit was carried out for different values of $B_s \in (-40, 0)$ MeV and $\Gamma \in (5, 50)$ MeV.

The obtained upper limit as a function of the B_s and Γ is presented in Fig. 6. The upper limit value varies between 18 to 33 nb and depends mainly on the width of the bound state, while it is not sensitive to the binding energy.

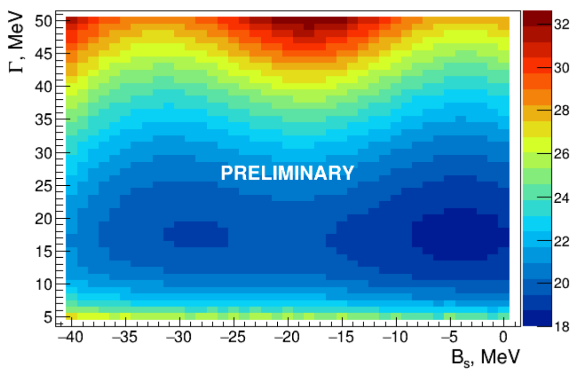

Fig. 6. Upper limit of the total cross section as a function of different B_s and Γ.

4. Outlook

In 2014, we performed a search for the η-mesic helium in proton–deuteron collisions with the WASA-at-COSY detector. The preliminary excitation function, determined for the $pd \to pd\pi^0$ reaction, does not reveal a narrow structure which could be interpreted as a signature of the mesic nucleus. The preliminary upper limit of the total cross sections for the bound state production and decay in this process was calculated and is equal to 18–33 nb. The analysis of the $pd \to ppn\pi^0$ and $pd \to ppp\pi^-$ channels is in progress.

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REFERENCES

[1] Q. Haider, L.C. Liu, *Phys. Lett. B* **172**, 257 (1986).

[2] M. Skurzok *et al.*, *Nucl. Phys. A* **993**, 121647 (2020).

[3] N.G. Kelkar *et al.*, *Nucl. Phys. A* **996**, 121698 (2020).

[4] N.G. Kelkar *et al.*, *Int. J. Mod. Phys. E* **28**, 1950066 (2019).

[5] N.G. Kelkar *et al.*, *Rep. Progr. Phys.* **76**, 066301 (2013).

[6] N.G. Kelkar, *Acta Phys. Pol. B* **46**, 113 (2015).

[7] N.G. Kelkar, *Eur. Phys. J. A* **52**, 309 (2016).

[8] C. Wilkin *et al.*, *Phys. Lett. B* **654**, 92 (2007).

[9] C. Wilkin, *Acta Phys. Pol. B* **47**, 249 (2016).

[10] S.D. Bass, P. Moskal, *Rev. Mod. Phys.* **91**, 015003 (2019).

[11] S.D. Bass, A.W. Thomas, *Phys. Lett. B* **634**, 368 (2006).

[12] S.D. Bass, A.W. Thomas, *Acta Phys. Pol. B* **45**, 627 (2014).

[13] N. Barnea, E. Friedman, A. Gal, *Phys. Lett. B* **747**, 345 (2015).

[14] N. Barnea, B. Bazak, E. Friedman, A. Gal, *Phys. Lett. B* **771**, 297 (2017).

[15] N. Barnea, E. Friedman, A. Gal, *Nucl. Phys. A* **968**, 35 (2017).

[16] E. Friedman, A. Gal, J. Mares, *Phys. Lett. B* **725**, 334 (2013).

[17] S. Wycech, W. Krzemień, *Acta Phys. Pol. B* **45**, 745 (2014).

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

[19] B. Krusche *et al.*, *J. Phys. Conf. Ser.* **349**, 012003 (2012).

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

[21] V. Metag, M. Nanova, E.Ya. Paryev, *Prog. Part. Nucl. Phys.* **97**, 199 (2017).

[22] M. Skurzok, P. Moskal, W. Krzemień, *Prog. Part. Nucl. Phys.* **67**, 445 (2012).

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

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

[25] M. Skurzok *et al.*, *Phys. Lett. B* **782**, 6 (2018).

[26] M. Skurzok, *Acta Phys. Pol. B* **51**, 33 (2020).

[27] M. Skurzok *et al.*, *Nucl. Phys. A* **993**, 121647 (2020).

[28] P. Adlarson *et al.*, *Phys. Lett. B* **802**, 135205 (2020).

[29] O. Rundel *et al.*, *EPJ Web Conf.* **199**, 02029 (2019).

[30] A. Khreptak *et al.*, *Acta Phys. Pol. B* **51**, 361 (2020).

[31] A. Khreptak *et al.*, *EPJ Web Conf.* **199**, 05026 (2019).

[32] H.-H. Adam *et al.*, `arXiv:nucl-ex/0411038`.