SEARCH FOR THE η-MESIC HELIUM IN PROTON–DEUTERON REACTION*

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We briefly report on the search for η-mesic helium nuclei with WASA-at-COSY detection setup. The description of the experimental method as well as the status of the data analysis of the proton–deuteron reactions are presented.

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1. Introduction

Although the existence of η- and η'-mesic nuclei, in which the $\eta(\eta')$ meson is bound in a nucleus by means of the strong interaction, has been theoretically predicted many years ago [1–7]; this kind of exotic nuclear matter remains still not experimentally confirmed. Experiments performed so far provide only signals which might be interpreted as an indications of the η- and η'-mesic bound states [8–14] and constraints on the depth of the η'-nucleus potential [15]. Recent reviews and discussion on the mesic nuclei search one can find in Refs. [16–33].

One of the most recent experiments related to η-mesic nuclei have been performed in Forschungszentrum Jülich using the COSY beam. The measurements carried out by COSY-11 and COSY-ANKE collaborations result in the steep rise in the total cross section for $dp \to {}^3\mathrm{He}\,\eta$ [12, 13] process close to the kinematical threshold and in the constant value of measured tensor analysing power T_{20} [14]. The observations can be the strong evidence for the existence of a pole in the ${}^3\mathrm{He}\,\eta$ scattering matrix which can be associated with the possible η-mesic nucleus. Moreover, in the direct

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search, the eta-mesic nucleus was not found so far. The COSY-11 group estimated upper limits of the total cross section for the $dp \to (^3\mathrm{He}\text{–}\eta)_{\mathrm{bound}} \to dpp\pi^-$ and $dp \to (^3\mathrm{He}\text{–}\eta)_{\mathrm{bound}} \to {}^3\mathrm{He}\pi^0$ reactions to the values of 270 nb and 70 nb, respectively [34–37]. The COSY-GEM measurement of recoil-free $p(^{27}\mathrm{Al},^3\mathrm{He})\pi^- p' X$ process results in determination of the upper limit of the total cross section for the η-mesic magnesium production equal to 0.46±0.16(stat.)±0.06(syst.) nb [9].

The search for η-mesic helium is carried out with high statistics and high acceptance with the WASA-at-COSY detection system in deuteron–deuteron ($^4\mathrm{He}$–η) and proton–deuteron ($^3\mathrm{He}$–η) fusion reactions with the beam momentum changing slowly and continuously around the η-production threshold in each of COSY acceleration cycle. The $^4\mathrm{He}$–η-mesic nuclei were searched via studying of excitation function for the $dd \to {}^3\mathrm{He}p\pi^-$ [16, 38–40] (2008 and 2010 data) and $dd \to {}^3\mathrm{He}n\pi^0$ [16, 38, 41] (2010 data) reactions near the $^4\mathrm{He}\,\eta$ threshold.

Excitation functions determined for $dd \to {}^3\mathrm{He}p\pi^-$ and $dd \to {}^3\mathrm{He}n\pi^0$ processes do not reveal any direct narrow structure which could be signature of the bound state with width less than 50 MeV. The upper limit of the total cross section for the η-mesic $^4\mathrm{He}$ formation and decay was estimated for both processes taking into account the isospin relation between $n\pi^0$ and $p\pi^-$ pairs emerging from the N^* decay (the probability of $p\pi^-$ pair production is two times higher than in the case of $n\pi^0$ production). The upper limits vary from 2.5 to 3.5 nb for the first process and from 5 to 7 nb for the second process for the width ranging from 5 to 50 MeV. More details concerning presented results can be found in Refs. [38, 41].

2. Status for $^3\mathrm{He}$–η nuclei

The experiment dedicated to search for $^3\mathrm{He}$–η bound states was performed by the WASA-at-COSY Collaboration in 2014. During the measurement, the ramped proton beam with momentum changing continuously in the range of 1.426–1.635 GeV and pellet deuterium target were used. The range of the beam momentum corresponds to the range of excess energy $Q_{^3\mathrm{He}\,\eta}$ from −70 to +30 MeV. The $^3\mathrm{He}$–η bound states [16, 42] are searched in processes corresponding to the three mechanisms: *(i)* absorption of the η meson by one of the nucleons, which subsequently decays into N^*–π pair *e.g.*: $pd \to (^3\mathrm{He}\text{–}\eta)_{\mathrm{bound}} \to ppp\pi^-$, *(ii)* decay of the η meson while it is still "orbiting" around a nucleus *e.g.*: $pd \to (^3\mathrm{He}\text{–}\eta)_{\mathrm{bound}} \to {}^3\mathrm{He}\,6\gamma$ reactions and *(iii)* η-meson absorption by few nucleons *e.g.*: $pd \to (^3\mathrm{He}\text{–}\eta)_{\mathrm{bound}} \to ppn$.

The experimental luminosity can be determined in the whole beam momentum range based on $pd \to ppn_{\mathrm{spec}}$ reaction and, in addition, it can be also determined based on $pd \to {}^3\mathrm{He}\,\eta$ reaction in the range above η-production threshold ($Q_{^3\mathrm{He}\,\eta} > 0$). Luminosity estimation from $pd \to {}^3\mathrm{He}\,\eta$ reaction is the first stage of the data analysis. Events corresponding to this reaction were identified by ^{3}He tracks registered in the forward part of the WASA detector. For performing the analysis, identification of ^{3}He by ΔE–E method and reconstruction of kinetic energy from the energy deposited in the detector were carried out. The angles were reconstructed based on registered tracks with the algorithms implemented earlier by WASA-at-COSY team and used in the previous analysis *e.g.* [44].

For obtaining the amount of events corresponding to η creation, the ^{3}He missing mass spectra have been analysed for each of excess energy $Q_{^3\mathrm{He}\,\eta}$ intervals. These events are visible as a peak around the value equal to the mass of the η meson. The value of integrated luminosity for each $Q_{^3\mathrm{He}\,\eta}$ bin was obtained from the formula $L = \frac{N}{\epsilon\sigma}$, where the amount of events N is extracted from the η-creation peak area (Fig. 1), the acceptance ϵ is determined based on Monte Carlo simulation and the total cross section σ is taken from other experiments [43].

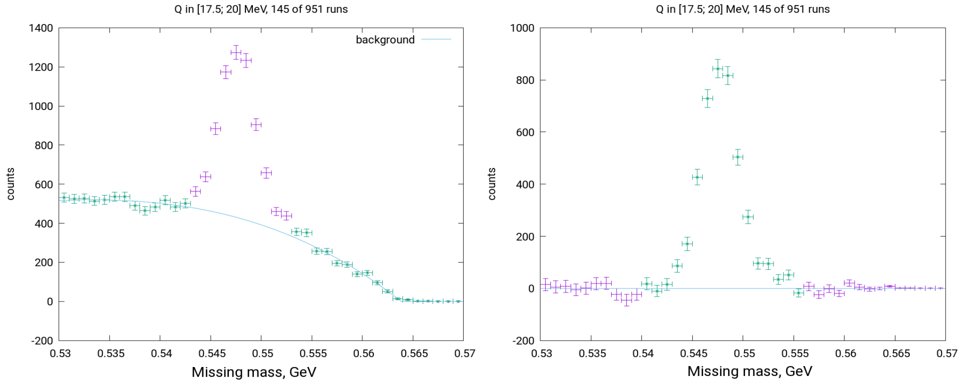

Fig. 1. The ^{3}He missing mass spectrum for the excess energy interval $Q_{^3\mathrm{He}\,\eta} \in (17.5, 20)$ MeV. Left: the background around the η-creation peak is fit with a polynomial. Right: missing mass after the background subtraction (for obtaining the amount of η creation events).

The obtained integrated luminosity for each $Q_{^3\mathrm{He}\,\eta}$ bin is shown in Fig. 2. Total integrated luminosity of about 3.7 pb^{-1} was estimated assuming that excess energy intervals for $Q_{^3\mathrm{He}\,\eta} < 0$ have the same values as determined for $Q_{^3\mathrm{He}\,\eta} > 0$ (about 14 nb^{-1}) and taking into account the amount of data that has not been analysed yet. If we estimate the time of measurement as 10^6 s, then the obtained value of average luminosity becomes 3.7 10^{30} cm^{-2} s^{-1}. This value is in agreement with the value given in the proposal [42].

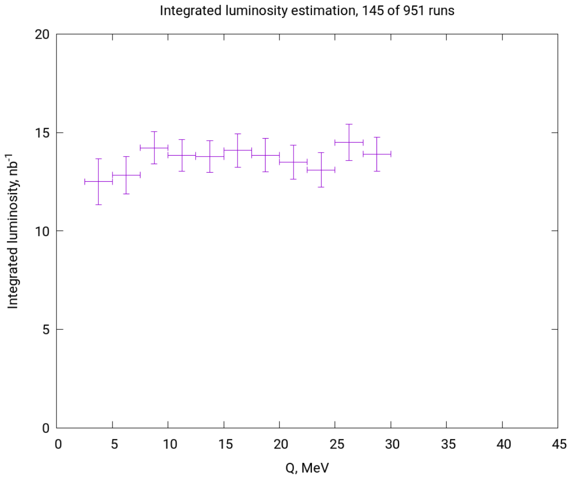

Fig. 2. Integrated luminosity determined based on $pd \to {}^{3}\mathrm{He}\,\eta$ reaction for the excess energy range of $Q_{^{3}\mathrm{He}\,\eta} > 0$. The luminosity was calculated for 8.5% of the collected data.

3. Conclusion and perspectives

The WASA-at-COSY Collaboration performed search for η-mesic helium in deuteron–deuteron and proton–deuteron reactions. Excitation functions determined for $dd \to (^{4}\mathrm{He}{-}\eta)_{\mathrm{bound}} \to {}^{3}\mathrm{He}p\pi^{-}$ and $dd \to (^{4}\mathrm{He}{-}\eta)_{\mathrm{bound}} \to {}^{3}\mathrm{He}n\pi^{0}$ processes do not reveal any direct narrow structure which could be a signature of the narrow bound state (width less than 50 MeV). Therefore, the upper limit of the total cross section for the η-mesic ^{4}He formation and the decay was estimated based on data collected in 2010.

In May 2014, the search was extended to the $^{3}\mathrm{He}{-}\eta$ sector [42]. In case if such bound state exists, one of its decays mechanisms can be the direct decay of orbiting η into two or six γ-quanta. This process can be visible in $pd \to^{3}\mathrm{He}\,2\gamma$ and $pd \to {}^{3}\mathrm{He}\,6\gamma$ reactions. If there is no bound state, these reactions will be visible only above the η-creation threshold, otherwise essential events amount below the threshold will point the bound state decays. Another possible mechanism of bound state decay is the single- or multi-nucleon absorption of η and then decay of the compound system. Absorption of η in one of nucleons, which subsequently decays into $N{-}\pi$ pair would result in *e.g.* $pd \to ppp\pi^{-}$ and $pd \to ppn\pi^{0}$ reactions, while the η-meson absorption by few nucleons in $pd \to (^{3}\mathrm{He}{-}\eta)_{\mathrm{bound}} \to ppn$ or $pd \to (^{3}\mathrm{He}{-}\eta)_{\mathrm{bound}} \to pd$ processes. The η-mesic nuclei would be visible as a resonant structure below the η-production threshold.

Almost two weeks of measurement in 2014 allowed us to collect a world's largest data sample for the search of $^{3}\mathrm{He}\,\eta$ mesic nucleus. The total integrated luminosity was estimated for whole measurement and is equal to about 3.7 pb^{-1}. The data analysis is in progress.

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