Review

Search for the He-η bound states with the WASA-at-COSY facility

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A R T I C L E   I N F O

A B S T R A C T

The existence of η-mesic nuclei in which the η meson is bound with nucleus by means of the strong interaction was postulated already in 1986, however till now no experiment confirmed it empirically. Discovering of this new kind of an exotic nuclear matter would be very important as it might allow for better understanding of the η meson structure and its interaction with nucleons. The search for η-mesic helium (^{4}He-η) is carried out with high statistic and high acceptance by means of the WASA detector, installed at the cooler synchrotron COSY in the Research Center Jülich. The search is conducted via the measurement of the excitation function for the chosen decay channels of the ^{4}He-η system. In the experiment performed in November 2010 two reactions $dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}p\pi^-$ and $dd \rightarrow (^4\text{He-}\eta)_{bs} \rightarrow {}^3\text{He}n\pi^0$ were measured with the beam momentum ramped from 2.127 GeV/c to 2.422 GeV/c. The report includes the description of experimental method and status of the measurement.

1. Introduction

As early as in 1985 Bhalerao and Liu [1] performed a coupled-channel analysis of the $\pi N \rightarrow \pi N$, $\pi N \rightarrow \pi \pi N$ and $\pi N \rightarrow \eta N$ reactions in the close-to-threshold region, and discovered that the interaction between the nucleon and the η meson is attractive. This finding inspired Haider and Liu to postulate the existence of the η-mesic nuclei [2], in which the neutral η meson might be bound with nucleons via the strong interaction. The existence of η-mesic bound states would allow to investigate the interaction of the η meson and nucleons inside a nuclear matter. Moreover it would provide information about the N*(1535) resonance [3] and about the η meson properties in a nuclear matter [4], as well as about the contribution of the flavour singlet component of the quark–gluon wave function of the η meson [5,6]. According to the theoretical considerations, the formation of the η-mesic nucleus can only take place if the real part of the η-nucleus scattering length is negative (attractive nature of the interaction), and the magnitude of the real part is greater than the magnitude of the imaginary part [7]:

$$|\text{Re}(a_{\eta\text{-nucleus}})| > |\text{Im}(a_{\eta\text{-nucleus}})|. \tag{1}$$

A wide range of possible values of the s-wave ηN scattering length, from $a_{\eta N} = (0.27 + 0.22i)$ fm up to $a_{\eta N} = (1.05 + 0.27i)$ fm, calculated for hadronic- and photoproduction of the η meson has not excluded the formation of η-nucleus bound states for a light nuclei as ^{3,4}He, T [8,9] and even for deuteron [10]. Those bound states have been searched for in many experiments [11–17], however none of them gave empirical confirmation of their existence. There are only promising experimental observations which might be interpreted as indications of the η-mesic nuclei. For example, experimental observations which might suggest the possibility of the existence of the ^{3}He-η bound system were found by

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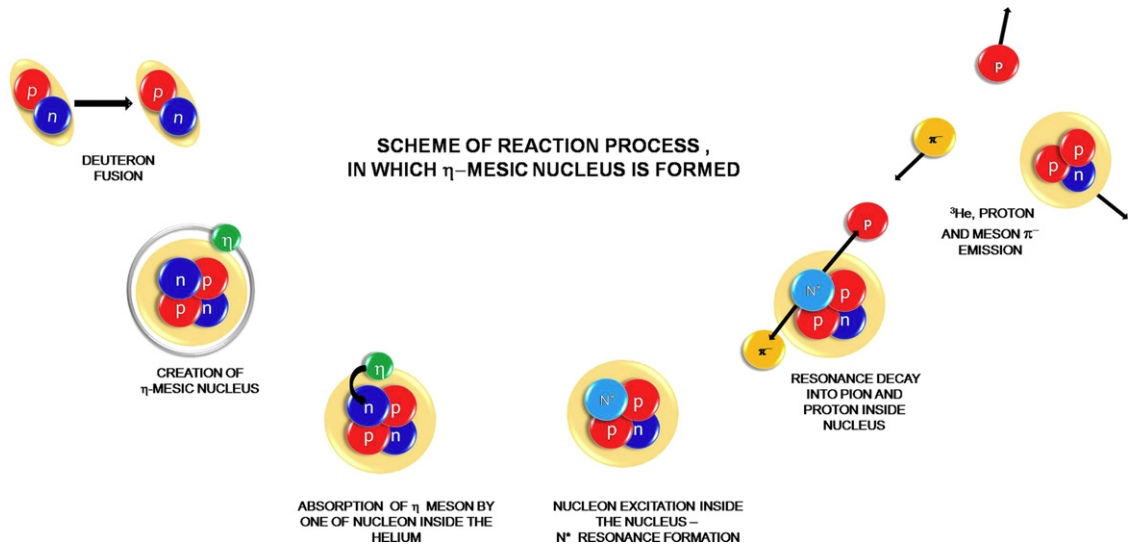 *E-mail address:* mskurzok@gmail.com (M. Skurzok).

Fig. 1. Reaction process of the (^{4}He-η)$_{bs}$ production and decay.

SPES-4 [14], SPES-2 [15], ANKE [16] and COSY-11 [17] collaborations. The data analysis of the close to threshold SPES-4 and SPES-2 measurements of the total cross section led to the determination of the η^3He scattering length which within the experimental errors fulfill the condition given by Eq. (1). In the experiments conducted at the COSY synchrotron the momentum ramping technique of the deuteron beam was used that allows to reduce the systematic uncertainties [18]. The beam was accelerated slowly and linearly in time, from excess energy of $Q = -5.05$ MeV up to $Q = 11.33$ MeV in case of the ANKE experiment [16], while during the COSY-11 experiment [17] the momentum was varied in the range corresponding to the excess energy from $Q = -10$ MeV to $Q = 9$ MeV. Both collaborations performed the measurement of the excitation function and differential cross section of the $dp \rightarrow \ ^3$He-η reaction close to the kinematical threshold. Data taken by the COSY-11 group were used to search for a signal of a ^{3}He-η bound state below the η production threshold of the $dp \rightarrow ppp\pi^-$ and $dp \rightarrow \ ^3$Heπ^0 reactions [19–21], while the measurements above the threshold enabled the study of the forward–backward asymmetries of the differential cross sections and the extraction of the η-^{3}He scattering length. The data of both groups [16,17] shows a variation in the phase of the *s*-wave amplitude in the near-threshold region, consistent with the possible existence of a bound state [22].

The first direct experimental indications of light η-nucleus bound states were observed in the reaction of the η photoproduction γ^3He $\rightarrow \pi^0 pX$ which was carried out by the TAPS collaboration [23]. The measurements of the excitation functions for two ranges of the relative angle between π^0 and proton were carried out. It appeared that a difference between those excitation curves in the center-of-mass frame revealed an enhancement just below the threshold of the γ^3He $\rightarrow \ ^3$He-η reaction which was interpreted as a possible signature of a ^{3}He-η bound state where an η meson captured by one of nucleons inside helium forms an intermediate $S_{11}(1535)$ resonance which decays into a $\pi^0 - p$ pair. However, it was shown later that the result may be an artefact due to the strong influence of the resonances on the shape of the excitation function [24]. Therefore, a new high-statistics direct measurement is necessary.

2. Experiment

The measurement of the ^{4}He-η bound states is performed with unique precision at the COSY accelerator by means of the WASA detection system. Signals of the η-mesic nuclei are searched for via studying the excitation function of specific decay channels of the ^{4}He-η system, formed in deuteron–deuteron collision [25,26]. The measurement is performed for the beam momenta varying continuously around the η meson production threshold. The beam ramping technique allows to reduce the systematic uncertainties. The existence of the bound system should manifest itself as a resonance-like structure in the excitation curve of e.g. the $dd \rightarrow (^4$He-$\eta)_{bs} \rightarrow \ ^3Hep\pi^-$ reaction below the $dd \rightarrow \ ^4$He-η reaction threshold. The kinematics of the reaction is schematically presented in Fig. 1. The deuteron beam—deuteron target collision leads to the creation of the ^{4}He nucleus bound with the η meson via strong interaction. The η meson can be absorbed by one of the nucleons inside helium and may propagate in the nucleus via consecutive excitation of nucleons to the N*(1525) state [27] until the resonance decays into the pion–proton pair outgoing from the nucleus [28,29]. The relative angle between p and π^- is equal to 180° in the N* reference frame and it is smeared by about 30° in the center-of-mass frame due to the Fermi motion of the nucleons inside the helium nucleus.

In June 2008 a search for the ^{4}He-η bound state was performed by measuring the excitation function of the $dd \rightarrow \ ^3$He$p\pi^-$ reaction near the η production threshold. 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
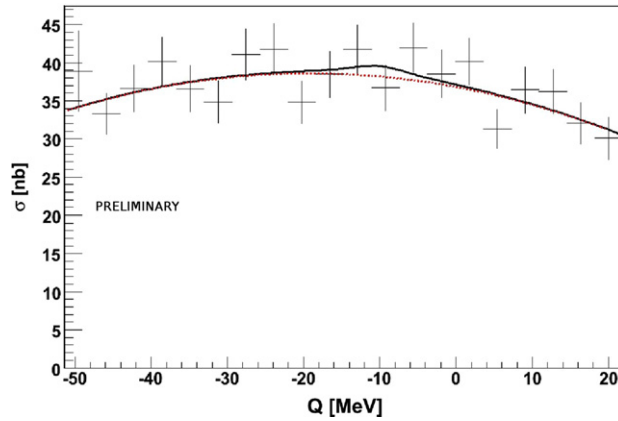
Fig. 2. Preliminary excitation function for the $dd \to {}^3\mathrm{He}p\pi^-$ reaction obtained by normalizing events selected in individual excess energy intervals by corresponding integrated luminosities. The solid line represents a fit with a second order polynomial combined with the Breit–Wigner 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 the acceptance end efficiency of cuts.
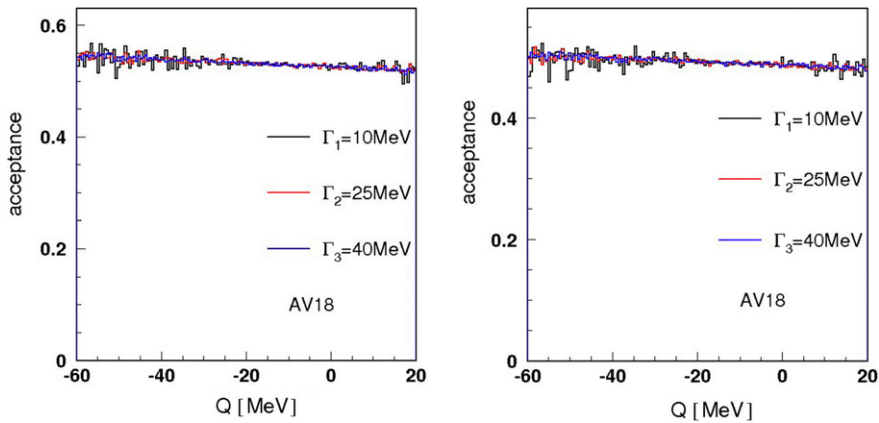

Fig. 3. Geometrical acceptances of the WASA-at-COSY detector for the $dd \to ({}^4\mathrm{He}\text{-}\eta)_{bs} \to {}^3\mathrm{He}p\pi^-$ (left) and $dd \to ({}^4\mathrm{He}\text{-}\eta)_{bs} \to {}^3\mathrm{He}n\pi^0 \to {}^3\mathrm{He}n\gamma\gamma$ reaction (right). Acceptance is calculated for three different bound state width values and the AV18 potential model describing the momentum distribution of the nucleons inside ${}^4\mathrm{He}$.

production in the $dd \to {}^4\mathrm{He}\eta$ reaction at 2.336 GeV/c. This range of beam momenta corresponds to the variation of ${}^4\mathrm{He}$-η excess energy from -51.4 MeV to 22 MeV. The excitation function was determined after applying cuts on the p and π^- kinetic energy distribution and the $p - \pi^-$ opening angle in the CM system [30]. The result is shown in Fig. 2.

The relative normalization of points of the $dd \to {}^3\mathrm{He}p\pi^-$ excitation function was based on the quasi-elastic proton–proton scattering. In the excitation function there is no structure which could be interpreted as a resonance originating from decay of the η-mesic ${}^4\mathrm{He}$.

During the experiment, in November 2010, two channels of the η-mesic helium decay were measured:
$dd \to ({}^4\mathrm{He}\text{-}\eta)_{bs} \to {}^3\mathrm{He}p\pi^-$ and $dd \to ({}^4\mathrm{He}\text{-}\eta)_{bs} \to {}^3\mathrm{He}n\pi^0 \to {}^3\mathrm{He}n\gamma\gamma$. The measurement was performed with the beam momentum ramping from 2.127 GeV/c to 2.422 GeV/c, corresponding to the range of the excess energy $Q \in (-70, 30)$ MeV.

For both reactions the geometrical acceptance of the detector as a function of the excess energy Q near the kinematical threshold for the η meson production was determined in simulations. It is presented in Fig. 3 for different bound state widths and AV18 models describing nucleon momentum distribution inside the ${}^4\mathrm{He}$ nuclei. The detailed description of the simulations is presented in Ref. [31].

The acceptance is almost a constant function of the excess energy and its average value is about 53% and 50% for $dd \to ({}^4\mathrm{He}\text{-}\eta)_{bs} \to {}^3\mathrm{He}p\pi^-$ and $dd \to ({}^4\mathrm{He}\text{-}\eta)_{bs} \to {}^3\mathrm{He}n\pi^0 \to {}^3\mathrm{He}n\gamma\gamma$, respectively. The high acceptance values allow high statistics measurements of these final states.

During the experiment in 2010, data were effectively taken for about 155 h. The average luminosity was estimated based on the trigger used for the elastic proton–proton scattering and is equal to about $L = 8.15 \cdot 10^{30}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Taking into account the fact that two reactions were measured, in total more than 40 times higher statistics were collected than in the experiment carried out in 2008.

3. Conclusion

The search for the ^{4}He-η bound states is performed with the WASA-at-COSY facility by taking advantage of its very high acceptance for the proton-π^- and neutron-π^0 pairs as well as very good identification of helium nuclei. In addition, WASA allows for an exclusive measurement of the $dd \rightarrow {}^3\text{He}p\pi^-$ reaction.

At present the data analysis is in progress. In the optimistic case, the statistics could be sufficient to observe a signal from the η-mesic helium and in the pesimistic scenario the upper limit of the cross section for the ^{4}He-η bound state production will be decreased by a factor of about six.

References

 [1] R.S. Bhalerao, L.C. Liu, Phys. Rev. C 54 (1985) 865.
 [2] Q. Haider, L.C. Liu, Phys. Lett. B 172 (1986) 257.
 [3] D. Jido, H. Nagahiro, S. Hirenzaki, Phys. Rev. C 66 (2002) 045202.
 [4] T. Inoue, E. Oset, Nuclear Phys. A 710 (2002) 354.
 [5] S.D. Bass, A.W. Thomas, Phys. Lett. B 634 (2006) 368.
 [6] S.D. Bass, A.W. Thomas, Acta Phys. Polon. B 41 (2010).
 [7] Q. Haider, L.C. Liu, Phys. Lett. C 66 (2002) 045208.
 [8] C. Wilkin, Phys. Rev. C 47 (1993) R938.
 [9] S. Wycech, A.M. Green, J.A. Niskanen, Phys. Rev. C 52 (1995) 544.
[10] A.M. Green, Phys. Rev. C 54 (1996) 1970.
[11] H. Machner, Acta Phys. Polon. B 41 (2010) 2221.
[12] G.A. Sokol, et al., arXiv:nucl-ex/0012010, 2000.
[13] A. Gillitzer, Acta Phys. Slovaca 56 (2006) 269.
[14] J. Berger, et al., Phys. Rev. Lett. 61 (1988) 919.
[15] B. Mayer, et al., Phys. Rev. C 53 (1996) 2068.
[16] T. Mersmann, et al., Phys. Rev. Lett. 98 (2007) 242301.
[17] J. Smyrski, et al., Phys. Lett. B 649 (2007) 258.
[18] P. Moskal, J. Smyrski, Acta Phys. Polon. B 41 (2010) 2281.
[19] J. Smyrski, et al., Acta Phys. Slovaca 56 (2006) 213.
[20] W. Krzemień, et al., Internat. J. Modern Phys. A 24 (2009) 576.
[21] J. Smyrski, et al., Nuclear Phys. A 790 (2007) 438.
[22] C. Wilkin, Phys. Lett. B 654 (2007) 92.
[23] M. Pfeiffer, et al., Phys. Lett. B 92 (2004) 252001.
[24] B. Krusche, et al., Acta Phys. Polon. B 41 (2010) 2249.
[25] P. Moskal, et al., Internat. J. Modern Phys. A 22 (2007) 305.
[26] W. Krzemień, arXiv:1101.3103, 2011.
[27] G.A. Sokol, et al., arXiv:nucl-ex/0106005, 2001.
[28] P. Moskal, arXiv:0909.3979, 2009.
[29] W. Krzemień, P. Moskal, J. Smyrski, Acta Phys. Pol. B. Proc. Suppl. 2 (2009) 141.
[30] W. Krzemień, Ph.D. Thesis, Jagiellonian University, 2011.
[31] M. Skurzok, Diploma Thesis, Jagiellonian University of Cracow, Berichte des FZ-Jülich, Jül-4332. arXiv:1009.5503, 2010.