Few-Body Syst 55:795–799
DOI 10.1007/s00601-013-0782-2

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Search for η-Mesic ^{4}He with WASA-at-COSY

Received: 6 November 2013 / Accepted: 16 December 2013 / Published online: 16 January 2014

Abstract An exclusive measurement of the excitation functions for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$ reactions was performed at the Cooler Synchrotron COSY-Jülich with the WASA-at-COSY detection system. The data were collected in two dedicated experiments in 2008 and in 2010. The experimental method and the current status of the analysis are presented.

1 Introduction

Over the years the studies of meson–nucleon interactions provided important information about the nature of the strong forces. However, because of the short lifetime of most of mesons the investigations can be performed only by studying the final state interaction of the meson with a nucleon or a nucleus.

In the case of the η meson, in the low energy region, where the η–N pairs are produced in s-wave, its interaction with nucleons is dominated by the excitation of the S_{11} resonance $N^*(1535)$ [1,2]. $N^*(1535)$ decays predominately into N–η and N–π with roughly equal probability. This feature suggests that the $N - \eta$ and N–π pairs should be treated as strongly coupled system and that the coupled channel formalism is an appropriate tool to describe it. In 1985, Bhalerao and Liu [3], performed coupled-channel calculations including N–η, N–π and Δ–π channels and showed that the s-wave η–N interaction is of strong and attractive nature. This result has raised the question whether the total interaction in a nucleus-η system is strong enough to form a bound-state.

The existence of η-mesic nuclei was suggested by Haider and Liu [4] in 1986. In contrast to the pionic bound states, the η-mesic nucleus is created exclusively due to the strong interaction. The bound state can be considered as a meson moving in the mean field of the nucleons in the nucleus.

The search for the η-mesic bound state has been and is being performed by many experiments [5–17], but so far no firm experimental confirmation of the existence of mesic nuclei has been achieved.

The observation of a strong enhancement in the total production cross-section and the phase variation of the scattering amplitude in the close-to-threshold region in the $dd \rightarrow {}^4\mathrm{He}\eta$ reaction are interpreted as a possible indication of a ^{4}He–η bound state [18,19]. This conclusion is supported by the predictions in References [20–23].

This study is conducted for the WASA-at-COSY collaboration.

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2 Method

We perform the search of a η-mesic helium produced in deuteron–deuteron collisions. One of the possible decay scenarios of the η–^{4}He bound state may proceed via the absorption of the η meson on one of the nucleons in the ^{4}He nucleus, leading to the excitation of the N^* (1535) resonance which subsequently decays in a pion-nucleon pair. The remaining three nucleons are spectators forming a ^{3}He or ^{3}H nucleus. This scenario is schematically presented in the Fig. 1.

The outgoing ^{3}He nucleus is a spectator and, therefore, we expect that its momentum in the c.m. frame is relatively low and can be approximated by the Fermi momentum distribution of nucleons inside the ^{4}He nucleus [24]. This signature allows us to suppress background from reactions with the same final state particles but without forming the intermediate $(^4\text{He}–\eta)_{bound}$ state and, therefore, resulting on average in much higher c.m. momenta of ^{3}He (see Fig. 2).

The process described above should result in a resonance-like structure in the excitation function of the $dd \rightarrow {}^3\text{He}p\pi^-$ and the $dd \rightarrow {}^3\text{He}n\pi^0$ reactions if we select events with low ^{3}He center-of-mass (c.m.) momenta. The maximum of the peak should lay below the η production threshold due to the mass deficit:

$$m_{bound} = m_{He} + m_\eta - E_{BE} \tag{1}$$

The mass and the binding energy of the bound state are denoted by m_{bound} and E_{BE}, respectively. The symbols m_{He} and m_η denote masses of ^{4}He and of η.

According to the discussed scheme, there exist four equivalent decay channels of the $(^4\text{He}–\eta)_{bound}$ state: $(^4\text{He}–\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$, $(^4\text{He}–\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0$, $(^4\text{He}–\eta)_{bound} \rightarrow {}^3\text{H}p\pi^0$, $(^4\text{He}–\eta)_{bound} \rightarrow {}^3\text{H}n\pi^+$.

In our experiment we concentrated on the first two out of the listed decay modes.

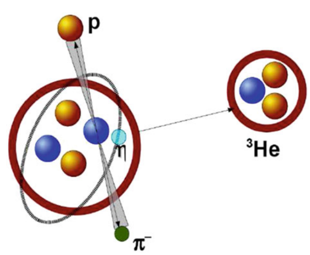

Fig. 1 Schematic picture of the $(^4\text{He}–\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ decay. In the first step the η meson is absorbed on one of the neutrons and the $N^\star$ resonance is formed. Next, the N* decays into a $p - \pi^-$ pair. The ^{3}He is a spectator

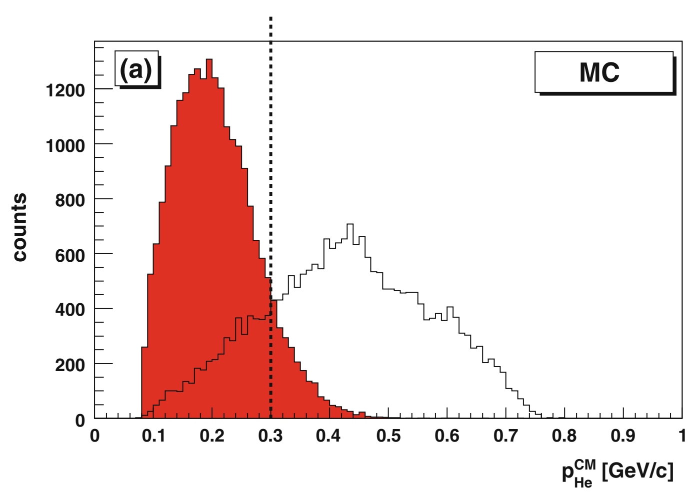

Fig. 2 Distribution of the ^{3}He momentum in the c.m. system simulated for the processes leading to the creation of the ^{4}Heη bound state: $dd \rightarrow (^4\text{He}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ (*red area*) and of the phase-space $dd \rightarrow {}^3\text{He}p\pi^-$ reaction (*black line*) (colour figure online)

3 The Experiment

We are carrying out a search for η-mesic helium with the WASA detector, installed at the cooler synchrotron COSY of Forschungszetrum Jülich [25]. The measurement is performed using the ramped beam technique which consists of a slow acceleration of the beam crossing the kinematic threshold for the η meson production in every cycle. The beam ramping technique allows us to reduce systematic uncertainties.

Two experiments dedicated to the search of the η-mesic helium were conducted up to now using the WASA-at-COSY detector. The first one was performed in June 2008 by measuring the excitation function of the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ reaction near the η meson production threshold [26].

The analysis does not show any structure which could be interpreted as a resonance originating from the decay of the η-mesic ^{4}He. The upper limit for the cross-section for the bound state formation and decay in the process $dd \rightarrow ({}^4\mathrm{He}\text{–}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ was determined at the 90 % confidence level and it varies from 20 to 27 nb for the bound state width ranging from 5 to 35 MeV, respectively. The upper limits depend mainly on the width of the bound state and only slightly on the binding energy.

During the second experiment, in November 2010, two channels of the η-mesic helium decay were measured: $dd \rightarrow ({}^4\mathrm{He}\text{–}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow ({}^4\mathrm{He}\text{–}\eta)_{bound} \rightarrow {}^3\mathrm{He}n\pi^0 \rightarrow {}^3\mathrm{He}n\gamma\gamma$ [10]. The momentum of the deuteron beam was varied continuously within each acceleration cycle from 2.127 to 2.422 GeV/c, crossing the kinematic threshold for η production in the $dd \rightarrow {}^4\mathrm{He}\,\eta$ reaction at 2.336 GeV/c. This range of beam momenta corresponds to a variation of the ^{4}He–η excess energy from −70 to 30 MeV.

Data were taken for about 155 h. The average luminosity was estimated based on the trigger rate for the elastic proton-proton scattering ($L = 8.15 \times 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). The ^{3}He was identified in the Forward Detector based on the ΔE-E method. The energy loss in the Plastic Scintillator Barrel was combined with the energy deposited in the Electromagnetic Calorimeter to identify negatively charged pions (Fig. 3).

The neutral pion was reconstructed in the Central Detector from the invariant mass of two gamma quanta originating from its decay (Fig. 4, left panel). Next, the neutron four-momentum is calculated using the missing mass technique (Fig. 4, right panel).

4 Summary

We are performing a search for a ^{4}He–η bound state by measuring the excitation function for the $dd \rightarrow {}^3\mathrm{He}p\pi^-$ and $dd \rightarrow {}^3\mathrm{He}n\pi^0$ reactions carried out with the WASA-at-COSY detector.

In the analysis of 2008 data no signal from a η-mesic ^{4}He was observed. The cross-section upper limit for the bound state formation and decay in the process $dd \rightarrow ({}^4\mathrm{He}\text{–}\eta)_{bound} \rightarrow {}^3\mathrm{He}p\pi^-$ was determined at the 90 % confidence level and it varies from 20 to 27 nb for the bound state width ranging from 5 to 35 MeV, respectively.

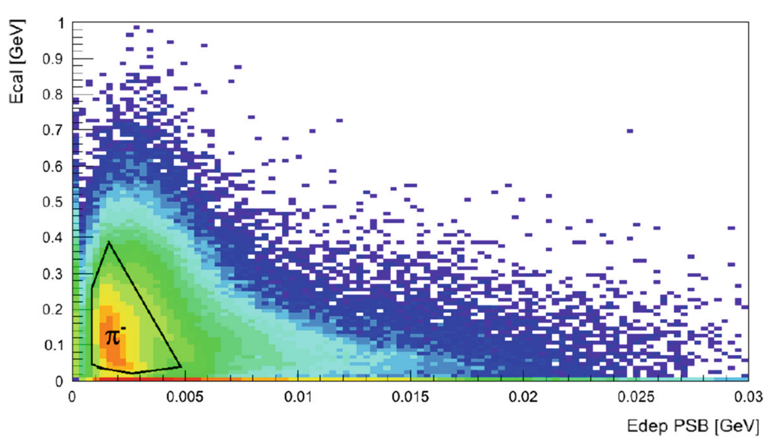

Fig. 3 Experimental distribution of the energy loss in the Plastic Scintillator Barrel (x-axis) combined with the energy deposited in the Electromagnetic Calorimeter (y-axis). The *lines* indicate the graphical condition applied to select pion candidates

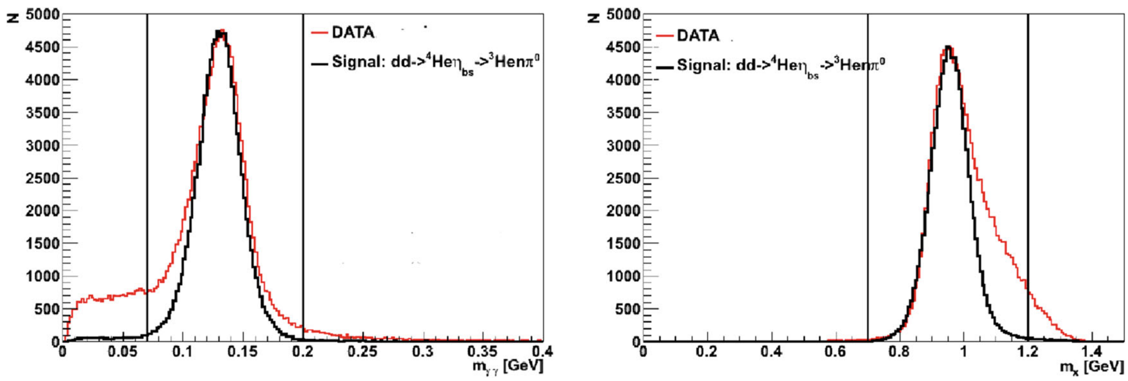

Fig. 4 (*left*) Distribution of the invariant mass of two gamma quanta. The *black vertical lines* indicate the conditions applied to select pion candidates. (*right*) Distribution of the missing mass of ^{3}Heπ^0. A pronounced peak corresponding to the neutron mass is visible. The *black vertical lines* indicate the selection of the neutron candidates. The experimental spectra are depicted by the *red curves* while MC simulations are shown in *black* (colour figure online)

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 also registered the $dd \rightarrow {}^3\mathrm{He}n\pi^0$ reaction.

The analysis of the new data is in progress.

Acknowledgments This work has been supported by FFE funds of Forschungszetrum Jülich, by the European Commission under the 7th Framework Programme through the 'Research Infrastructures' action of the 'Capacities' Programme. Call: FP7-INFRASTRUCTURES-2008-1, Grant Agreement No. 227431 and by the Polish National Science Center under Grants Nos. 0320/B/H03/2011/40 and 2011/01/B/ST2/00431, 2011/03/B/ST2/01847, 0312/B/H03/2011/40 and by the Foundation for Polish Science (MPD).

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