PROCEEDINGS OF SCIENCE

Search for η-mesic ^{4}He with the WASA-at-COSY detector

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We conduct a search for the He $-\eta$ bound state with WASA-at-COSY facility, via measurement of the excitation functions for the two reaction channels: $dd \to {}^3\mathrm{He}p\pi^-$ and $dd \to {}^3\mathrm{He}n\pi^0$, where the outgoing $N-\pi$ pairs originate from the conversion of the η meson on a nucleon inside the He nucleus. Two dedicated experiments were performed at the Cooler Synchrotron COSY-Jülich with the WASA-at-COSY detection system. The analysis of the data collected in 2008 is finished. No signal of the $^4\mathrm{He}-\eta$ bound state was observed. The shape of the excitation function for the $dd \to^3\mathrm{He}p\pi^-$ was examined. An upper limit for the cross-section for the bound state formation and decay in the process $dd \to (^4\mathrm{He}-\eta)_{bound} \to^3\mathrm{He}p\pi^-$, was determined on the 90 % confidence level and it varies from 20 nb to 27 nb for the bound state width ranging from 5 MeV to 35 MeV, respectively. The integrated luminosity in both experiments was determined using the $dd \to^3\mathrm{He}n$ reaction. The new experiment with about 20 times larger statistics was performed in 2010. The analysis is ongoing.

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1. Introduction

Investigation of exotic objects in nuclear physics is a proven method for revealing many interesting properties of nuclear systems and for accessing to unexplored areas of physics. As an example, the studies of hypernuclei, which contain at least one hyperion, extends the nuclear research to the strangeness dimension and provides important information on the structure of nuclei and on the baryon-baryon interaction. Also, 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 effects due to spontaneous chiral symmetry breaking [1].

It is conceivable that neutral mesons such as $\eta, \bar{K}, \omega, \eta'$, J/Ψ [1, 2, 3, 4, 5] can form bound states with atomic nuclei. In this case the binding is exclusively due to the strong interaction and the bound state or *mesic nucleus* - can be considered as a meson captured in the mean field of the nucleons. Due to the strong attractive η-nucleon interaction [6, 7], the η-mesic nuclei are some of the most promising candidates for such states.

Experimental confirmation of the existence of 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 in-medium properties of the N^* resonance [8] and of the η meson [9]. It could also help to determine the flavour singlet component of the η wave function [10].

The existence of η-mesic nuclei was postulated in 1986 by Haider and Liu [11]. Experimental searches have been performed by several past experiments [12, 13, 14, 15, 16] while ongoing investigations continue at COSY [17, 18, 19, 20, 21, 22], JINR [5], J-PARC [23], MAMI [24] and are planned at GSI [25]. Many promising indications where reported, however, so far there is no direct experimental confirmation of the existence of mesic nuclei.

In the region of the light nuclei systems, such as e.g. η-He, 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 provided strong evidence for the existence of a pole in the scattering matrix which can correspond to a bound state [26]. In particular, a very strong final state interaction (FSI) is observed in the $dd \rightarrow ^4\text{He}\eta$ reaction close to kinematic threshold and is interpreted as a possible indication of $^4\text{He}-\eta$ bound state [27]. This suggests, that the $^4\text{He}-\eta$ system is a good candidate for the experimental study of a possible binding. This conclusion is strengthened by the predictions in Reference [6].

Taking into account the above arguments and the fact that in the light nuclei systems the bound states are expected to be much narrower compared to the case of the heavy nuclei [30], we performed a search for η-mesic ^{4}He at the Cooler Synchrotron COSY-Jülich with the WASA-at-COSY detector [31].

2. Method

In our experimental studies, we used deuteron-deuteron collisions at energies around the η production threshold for production of the $\eta - ^4\text{He}$ bound state. We expect that the decay of such a state proceeds 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 play the role of spectators and they are likely to bind forming a ^{3}He or

^{3}H nucleus. In the case of a similar system, the $^4_\Lambda$He hypernucleus, it was observed that in the π^- decay channel the decay mode $^4_\Lambda\text{He} \rightarrow {}^3\text{He}p\pi^-$ is dominant [32].

This scenario is schematically presented in the Fig. 1.

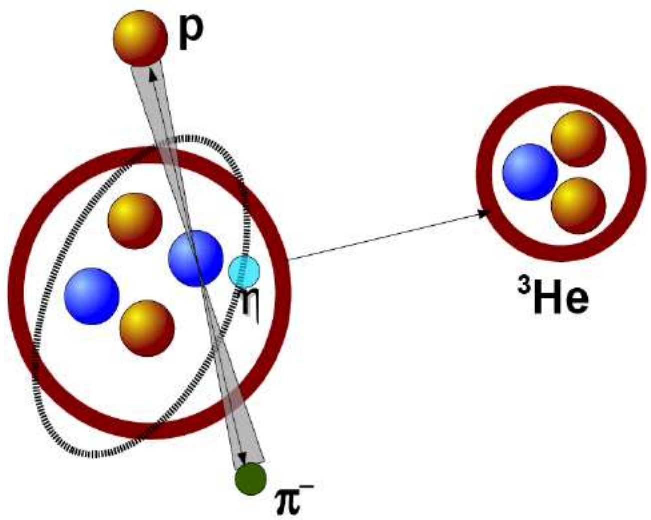

Figure 1: Schematic picture of the $(^4\text{He}-\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ decay. In the first step the η meson is absorbed on one of the neutrons and the $N^\star$ resonance is formed. Next, the N* decays into a $p-\pi^-$ pair. The ^{3}He plays the role of a spectator.

According to the discussed model, 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 experiments we concentrated on the $^3\text{He}p\pi^-$ and the $^3\text{He}n\pi^0$ decay modes .

The outgoing ^{3}He nucleus plays the role of 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 [33]. This signature allows us to suppress background from reactions leading to the $^3\text{He}p\pi^-$ and $^3\text{He}n\pi^0$ final state but proceeding without formation of the intermediate $(^4\text{He}-\eta)_{bound}$ state and, therefore, resulting on the average in much higher c.m. momenta of ^{3}He (see Fig. 2).

The experiment is based on the measurement of the excitation function of the $dd \rightarrow {}^3\text{He}p\pi^-$ and the $dd \rightarrow {}^3\text{He}n\pi^0$ reactions for energies in the vicinity of the η production threshold and on the selection of events with low ^{3}He center-of-mass (c.m.) 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 below the threshold for the production of the $^4\text{He}-\eta$ system.

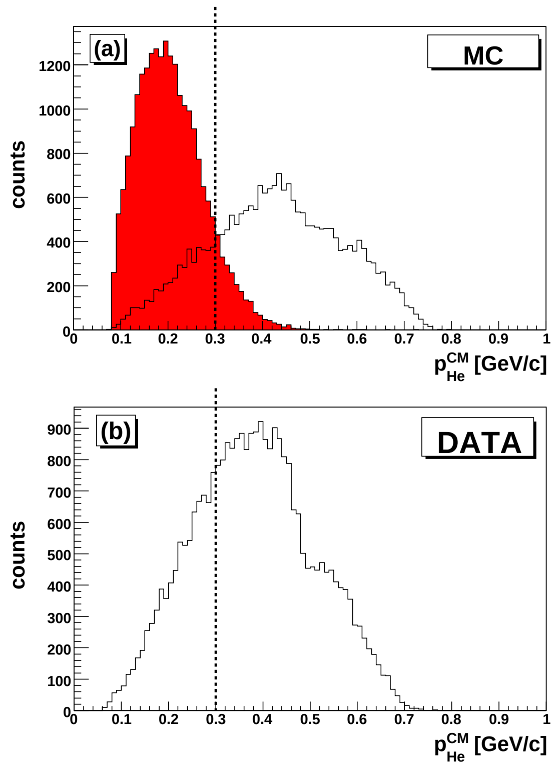

Figure 2: (Plot a) Distribution of the ^{3}He momentum in the c.m. system simulated for the processes leading to the creation of the ^{4}Heη bound state: $dd \to (^4\text{He}\eta)_{bound} \to ^3\text{He}p\pi^-$ (red area) and of the phase-space $dd \to ^3\text{He}p\pi^-$ reaction (black line). The simulation was done for a momentum of the deuteron beam of 2.307 GeV/c. The Fermi momentum parametrization was taken from [37]. (Plot b) Experimental distribution of the ^{3}He momentum in the c.m. system from the 2008 data. In both plots the dashed line demarcates the "signal-poor" and the "signal-rich" regions. The decrease of the counts at 0.48 GeV/c is due to the geometry of the border of the barrel and the end-caps of the Scintillator Barrel detector which was used in the $p-\pi^-$ identification process. This region has no relevance in the next steps of the analysis. From Ref. [34].

3. Results from the 2008 experiment

In June 2008 we performed a search for the η-mesic ^{4}He by measuring the excitation function of the $dd \to ^3\text{He}p\pi^-$ reaction near the η meson production threshold using the WASA-at-COSY detector. In this section, we summarize the main results. The full description of the analysis can be found in [34].

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 η production in the $dd \to ^4\text{He}\eta$ reaction at 2.336 GeV/c. This range of beam momenta corresponds to a variation of the $^4\text{He}-\eta$ excess energy from -51.4 MeV to 22 MeV.

The absolute value of the integrated luminosity in the experiment was determined using the $dd \to ^3\text{He}n$ reaction and the relative normalization of the points of the $dd \to ^3\text{He}p\pi^-$ excitation function was based on the quasi-elastic proton-proton scattering [38].

The luminosity as a function of the excess energy is shown as triangles in Fig. 3, it is flat within

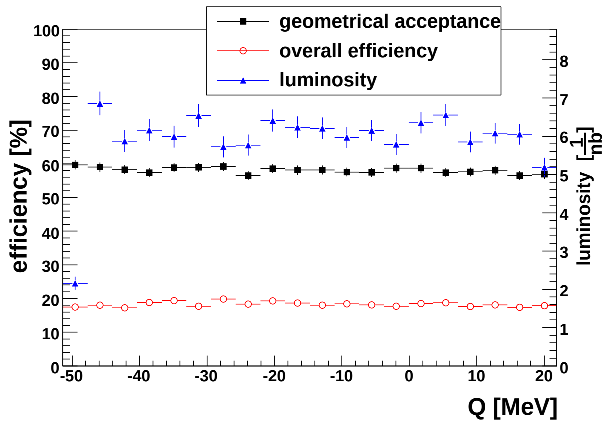

Figure 3: Geometrical acceptance (full black squares), overall efficiency (open red circles) and luminosity (full blue triangles) as a function of the excess energy. The right axis denotes the luminosity.From Ref. [34].

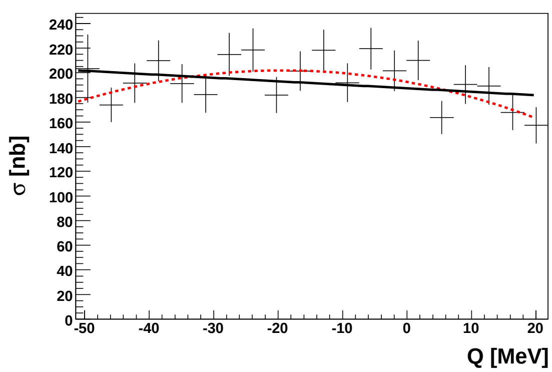

Figure 4: Experimental excitation function for the $dd \rightarrow ^{3}\mathrm{He} p \pi^{-}$ reaction obtained after the normalization of the events selected in individual excess energy intervals by the corresponding integrated luminosities. The dotted and solid lines correspond to the second and the first order polynomials fitted to the data. From Ref. [34].

the statistical uncertainties. The geometrical acceptance is about 60% and the overall efficiency including all selection conditions applied in the analysis is about 18% along the whole excess energy range. It is important to stress that both acceptance and efficiency are smooth and constant over the studied range.

The performed analysis exhibits no structure which could be interpreted as a resonance originating from the decay of the η-mesic ^{4}He.

The final excitation function obtained after the correction for the efficiency and the normalization to the luminosity is presented in Fig. 4. It can be well described by a second order polynomial (dashed line) resulting in a chi-squared value per degree of freedom of 0.98 and slightly worse by a straight line (solid line).

Since no signal originating from the formation of the $^{4}\mathrm{He}-\eta$ bound state was observed, we estimate an upper limit for its production via the $dd \rightarrow (^{4}\mathrm{He}\eta)_{bound} \rightarrow ^{3}\mathrm{He} p \pi^{-}$ reaction.

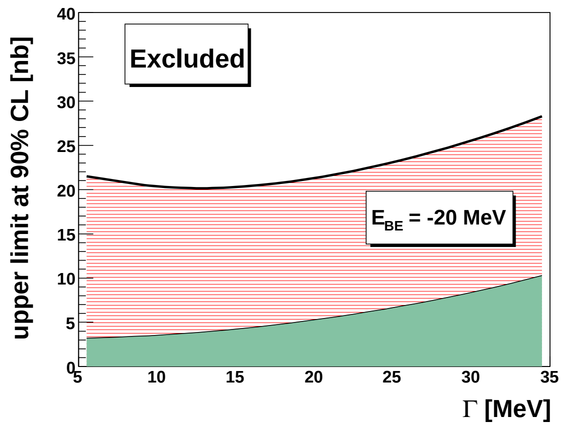

Figure 5: Upper limit at 90 % confidence level of the cross-section for formation of the ^{4}He$-\eta$ bound state and its decay via the $dd \rightarrow (^4\text{He}-\eta)_{bound} \rightarrow ^3\text{He}p\pi^-$ reaction as a function of the width of the bound state. The binding energy was set to E_{BE}=-20 MeV. The green area at the bottom represents the systematic uncertainties. From Ref. [34].

The result for E_{BE}=-20 MeV is shown in Fig. 5.

4. 2010 experiment

During the experiment, in November 2010, two channels of the η-mesic helium decay were measured: $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}p\pi^-$ and $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$ [18]. The measurement was performed with the beam momentum ramping from 2.127GeV/c to 2.422GeV/c, corresponding to the range of the excess energy Q∈(-70,30) MeV. Data were effectively taken for about 155 hours. The average luminosity was estimated based on the trigger used for the elastic proton-proton scattering and is equal to about L=$8.15 \cdot 10^{30} cm^{-2}s^{-1}$. 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.

Until now, only $dd \rightarrow (^4\text{He-}\eta)_{bound} \rightarrow {}^3\text{He}n\pi^0 \rightarrow {}^3\text{He}n\gamma\gamma$ reaction has been analysed. The ^{3}He was identified in the Forward Detector based on the ΔE-E method. The neutral pion π^0 was reconstructed in the Central Detector from the invariant mass of two gamma quanta originating from its decay while the neutron four-momentum was calculated using the missing mass technique.

The luminosity is determined based on the $dd \rightarrow {}^3\text{He}n$ reaction. The ^{3}He ions are identified via energy losses in the thick scintillator layers of the detector.

The number of $dd \rightarrow {}^3\text{He}n$ events is determined from the missing mass spectrum. To reject three and four-body reactions we take into account only events which give no more than one neutral cluster in the Central Detector. Monte Carlo simulations show that using this condition only about 6% of $dd \rightarrow {}^3\text{He}n$ events are rejected. Therefore, it allows to considerably reduce the background without significant loss of signal counts. The analysis and the study of systematics of the applied cuts are in progress. Luminosity will be determined as a function of $cos\theta_{cm}$ and the excess energy Q.

5. Summary

We perform a search for the ^{4}He$-\eta$ bound state via the measurement of the excitation function for the $dd \rightarrow ^3\mathrm{He}p\pi^-$ and the $dd \rightarrow ^3\mathrm{He}n\pi^0$ reactions. The measurement was carried out with the internal deuteron beam of the COSY accelerator scattered on a deuteron pellet target and with the WASA-at-COSY detection system used for registration of the reaction products.

In the measurement of 2008 for the first time in the experimental search for mesic nuclei all ejectiles were measured and the reaction was identified exclusively.

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

The upper limits depend mainly on the width of the bound state and only slightly on the binding energy.

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. 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 pessimistic 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.

6. Support

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