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Search for η-mesic helium using WASA-at-COSY

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Abstract. The installation of the WASA detector at the cooler synchrotron COSY opened the possibility to search for η-mesic helium with high statistics and high acceptance. A search for the $^4\mathrm{He}-\eta$ bound state is conducted via an exclusive measurement of the excitation function for the $dd \to {}^3\mathrm{He}\,p\pi^-$ reaction varying continuously the beam momentum around the threshold for the $dd \to {}^4\mathrm{He}\,\eta$ reaction. Ramping of the beam momentum and taking advantage of the large acceptance of the WASA detector allows to minimize systematical uncertainities.

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INTRODUCTION

In 1996 Yamazaki et al. discovered a bound state formed out of a π^- meson and a ^{207}Pb nucleus [1]. The negatively charged pion was bound with the lead nucleus by means of the Coulomb interaction and the interplay between an attractive Coulomb and a repulsive strong potential lead to the very narrow state with the width of less than one MeV. Due to the nature of the binding we can consider the state as a pionic atom.

It is also conceivable that a neutral meson could be bound to a nucleus. In this case the binding is exclusively due to the strong interaction and hence such object can be called a *mesic nucleus*. Here the most promising candidate is the η-mesic nucleus since the ηN interaction is attractive and since there exists a baryonic resonance (N$^*(1535)$) which couples predominantly to the ηN channel [2]. We may picture [3] the formation and decay of the η-mesic nucleus as the η meson absorption by one of the nucleons and then its propagation in the nucleus via subsequent excitation of nucleons to the N$^*(1535)$ state until the resonance decays into the pion-nucleon pair which escapes from the nucleus. Predicted values of the width of such states range from $\sim$7 to $\sim$40 MeV [4, 5, 6].

The search of the η - mesic nucleus was conducted in many inclusive experiments [7, 8, 9, 10, 11, 12, 13] via reactions induced by pions [7, 8], protons [10, 12], and photons [9, 13]. Many promising indications of the existence of such an object were reported [9, 13, 12], but so far none was independently confirmed. Experimental investigations with higher statistical sensitivity and the detection of the N$^*(1535)$ decay products are being continued at the COSY [14, 15], JINR [10], and MAMI [16] laboratories. In this contribution we report on searches of the η - mesic helium in exclusive measurements carried out at the cooler synchrotron COSY by means of the WASA-at-COSY [14, 15] and COSY-11 [17, 18, 19, 20] detector setups.

We consider the study of the η-mesic nuclei as interesting on its own account, but additionally it is useful for investigations of (i) the ηN interaction, (ii) the N$^*(1535)$ properties in nuclear matter [21], (iii) the properties of the η meson in the nuclear medium [22], and (iv) the flavour singlet component of the η meson [23].

INDICATIONS FOR THE EXISTENCE OF THE η - MESIC HELIUM

In 1985 Bhalerao and Liu [24] performed a coupled-channel analysis of the $\pi\mathrm{N} \to \pi\mathrm{N}$, $\pi\mathrm{N} \to \pi\pi\mathrm{N}$ and $\pi\mathrm{N} \to \eta\mathrm{N}$ reactions and discovered that the interaction between the nucleon and the η meson is attractive. Based on this finding Haider and Liu postulated the existence of the η–mesic nuclei [25], in which the electrically neutral η meson might be bound with the nucleons by the strong interaction. The formation of such a bound state can only take place if the real part of the η-nucleus scattering length is negative (attraction), and the magnitude of the real part is greater than the magnitude of the imaginary part [5, 26]. In the 1980's the η–mesic nuclei were considered to exists for $A \geq 12$ only [25] due to the relatively small value of the ηN scattering length ($a_{\eta\mathrm{N}} = (0.28 + i0.19)$ fm [24]). However, recent theoretical investigations of hadronic- and photo-production of the η meson result in values of $a_{\eta\mathrm{N}}$

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which depending on the analysis method range from $a_{\eta N} = (0.25 + i0.16)$ fm up to $a_{\eta N} = (1.05 + i0.27)$ fm [27], and which do not exclude the formation of a bound η-nucleus states for such light nuclei as helium [28, 29] or even for deuteron [30]. According to the calculations including multiple scattering theory [29] or Skyrme model [31] an especially good candidate for binding is the $^4\mathrm{He}-\eta$ system. Recent calculations by Haider [6] or Tryasuchev and Isaev [32] also indicate the binding in the $^4\mathrm{He}-\eta$ system, while they rather exclude the existence of the $^3\mathrm{He}-\eta$ state. On the other hand there are promissing experimental signals which may be interpreted as indications of the the $^3\mathrm{He}-\eta$ bound state. For example the shape of the excitation function for the $dp \rightarrow {}^3\mathrm{He}\,\eta$ reaction [28], determined by the SPES-4 [33], SPES-2 [34], COSY-11 [35], and COSY-ANKE [36] collaborations (Fig. 1(left)). It has been

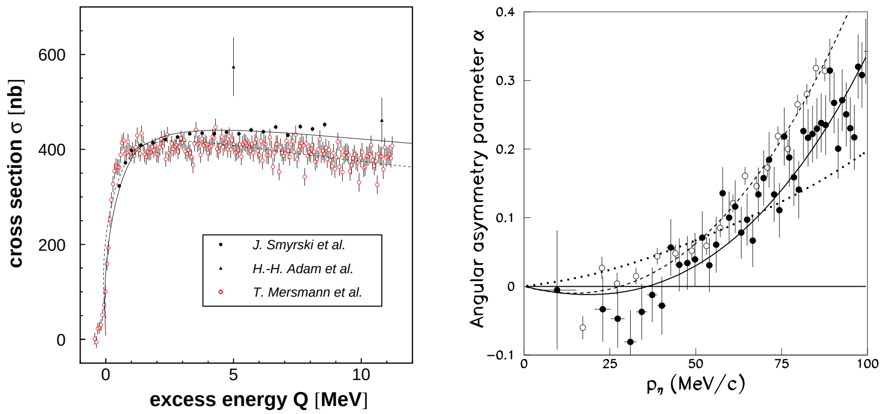

FIGURE 1. (left) Total cross section for the $dp \rightarrow {}^3\mathrm{He}\eta$ reaction as determined by the COSY-ANKE [36] (open circles) and the COSY-11 [35] (full dots) and [37] (triangles). The solid and dashed lines represent the scattering length fit to the COSY-11 and COSY-ANKE data, respectively. (right) Angular asymmetry parameter α. Closed and open circles represent results of COSY-ANKE [36] and COSY-11 [35], respectively. The dashed and solid lines denote results [38] of the fit (allowing for the phase variation) to the COSY-11 and COSY-ANKE data, respectively. The dotted line denotes result of the fit without the phase variation. The figure is adopted from Ref. [38].

indicated by Wilkin [38, 39] that a steep rise of the total cross section in the very close-to-threshold region followed by a plateau may be due to the existence of a pole of the $\eta^3\mathrm{He} \rightarrow \eta^3\mathrm{He}$ scattering amplitude in the complex excess energy plane Q with $Im(Q) < 0$ [38]. This reference shows that the occurence of the pole changes the phase and the magnitude of the s-wave production amplitude. And indeed the momentum dependence of the asymmetry in the angular distributions of $\cos\theta_\eta$ expressed in terms of a parameter α [35], can only be satisfactorily described (solid and dashed lines in Fig. 1 (right)) if a very strong phase variation associated with the pole is included in the fits [38, 39]. Otherwise there is a significant discrepancy between the experimental data and the theoretical description (dotted line in Fig. 1 (right)).

SEARCH OF THE $\eta -{}^4\mathrm{He}$ STATE WITH WASA-AT-COSY

The installation of the WASA detector at COSY opened a unique possibility to search for the $^4\mathrm{He}-\eta$ bound state with high statistics and high acceptance. We have conducted a search via an exclusive measurement of the excitation function for the $dd \rightarrow {}^3\mathrm{He}\,p\pi^-$ reaction varying continuously the beam momentum around the threshold for the $dd \rightarrow {}^4\mathrm{He}\,\eta$ reaction. Ramping of the beam momentum and taking advantage of the large acceptance of the WASA detector[1] allows to minimize systematical uncertainities making the WASA-at-COSY a unique facility [40] for such kind of exclusive experiments. The $^4\mathrm{He}-\eta$ bound state should manifest itself as a resonant like structure below the threshold for the $dd \rightarrow {}^4\mathrm{He}\,\eta$ reaction. If a peak below the $^4\mathrm{He}\,\eta$ threshold is found, then the profile of the excitation curve will allow to determine the binding energy and the width of the $^4\mathrm{He}-\eta$ bound state. If, however, only an enhancement around the threshold is found, then it will enable to establish the relation between width and binding

[1] For the coincidence registration of all ejectiles from the $dd \rightarrow (\eta\,{}^4\mathrm{He})_{bound} \rightarrow {}^3\mathrm{He}\,p\pi^-$ reaction the acceptance of the WASA-at-COSY detector equals to almost 70%.

energy [4]. Finally, if no structure is seen the upper limit for the cross section of the production of the η-helium nucleus will be set at few nanobarns. In addition, when searching for the signal of the η-mesic state we may take advantage of the fact that the distribution of the relative angle between the $nucleon - pion$ pair for the background (due to the prompt $dd \rightarrow {}^3\mathrm{He}\, p\, \pi^-$ reaction) is much broader than the one expected from the decay of the bound state. This is because the relative angle between the outgoing $nucleon - pion$ pair originating from the decay of the $\mathrm{N}^*(1535)$ resonance is equal to 180° in the N^* reference frame and it is smeared only by about 30° in the reaction center-of-mass frame due to the Fermi motion of the nucleons inside the He nucleus. This allows for an additional control of the background by comparing excitation functions corresponding to the "signal-rich" and "signal-poor" regions.

In the first experiment conducted in June 2008, we used a deuteron pellet target and the COSY deuteron beam with a ramped momentum corresponding to a variation of the excess energy for the ${}^4\mathrm{He} - \eta$ system from -51.4 MeV to 22 MeV. At present the data are evaluated and some preliminary results were reported [15]. The experiment will be continued in 2010 [14]. Two weeks of COSY beamtime were already recommended by the COSY Program Advisory Committee.

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