Production and interaction of the $\eta$ meson with nucleons and nuclei

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Abstract. We report on the status of the search for $\eta$-mesic nuclei and the studies of the interaction of the $\eta$ meson with nucleons. Recently we have completed the analysis of the new WASA-at-COSY data on the production of the $\eta$ meson with polarized proton beam. New results on the analyzing power for the $\vec{p}p \rightarrow pp\eta$ reaction with more than an order of magnitude improved precision shed a new light on the production mechanism of the $\eta$ meson in nucleon-nucleon collisions. Also, the latest results of the search for $\eta$-mesic nuclei are discussed.

1 Introduction

The $\eta$ particle together with isoscalar $\eta'$ and isovector $\pi^0$ lay in the origin ($S = 0$, $I_3 = 0$) of the nonet of pseudoscalar mesons representation. However, its behaviour is very different with respect to its interaction with nucleons [1]. In the low energy region, the $\eta$ meson interaction with nucleons is dominated by the $S_{11}$ resonance, which with its mass of 1535 MeV lays very close to the $\eta$-N threshold. This makes the s-wave $\eta-N$ interaction very strong and - as shown the analysis of Bhalerao and Liu - attractive [2]. This can be contrasted with the pion case which, dominated by the p-wave interaction from the $\Delta(1232)$ resonance, is much weaker [3]. Also, the measurement of the $\eta'N$ scattering length shows that its interaction is rather weak [4]. The large value of the $\eta-N$ scattering length led to the hypothesis, proposed by the Haider and Liu, who postulated that the total interaction in a nucleus- system is strong enough to form a bound-state - the so called mesic nuclei [5]. The second question raised and not unequivocally answered by the earlier measurements was about the $\eta$ production mechanism in the nucleon-nucleon collisions.

Due to the short lifetime of the meson ($t \approx 10^{-18}$ s) it is not feasible to create the $\eta$ beam. Therefore, its interaction with nucleons or nuclei must be studied via the observation of final states of nuclear reactions including the $\eta$-nucleon (or $\eta$-nuclei) pair. The Final State Interaction between produced particles can strongly influence the production cross-sections and, in this way, can be used for studies of the interaction itself [6].
In this contribution we discuss the $\eta$ production mechanism in the interaction with nucleons and the search for the $\eta$-mesic nuclei in the context of the recent experimental results from WASA-at-COSY collaboration.

## 2 $\eta$ production mechanism in the interaction with nucleons

The measurements of the large total cross-section of $NN \rightarrow NN\eta$ reaction near the $\eta$ production threshold [7–18] motivated the two-step $\eta$ production model proposed in [19]. In this scenario one of the proton is firstly excited through the exchange of a single meson and forms the $S_{11}$ resonance, which in the second step deexcites via the emission of $\eta$ and nucleon. In principle, the excitation to $S_{11}$ state can occur by exchanging $\pi$, $\eta$, $\omega$ or/and $\rho$ mesons. The measurements of total cross-section isospin dependence by WASA/PROMICE and COSY-11 showed that the $\eta$ production in the total isosinglet state is much higher that in the isotriplet state [18, 20]. This result strongly suggest the isovector meson exchange, reducing the candidates to $\pi$ and $\rho$ particles [19, 21, 22]. To further distinguish between the $\pi$ and $\rho$ meson exchange models, the determination of the analysing power in the polarization measurement was required. The first measurement by COSY-11 gave an indication in favour of the pseudoscalar exchange model, although due to the limited statistics the decisive conclusions could not be done [23–25]. The WASA-at-COSY performed a high-statistics measurement of the $\vec{p}p \rightarrow pp\eta$ with the polarized beam. The spin of the polarization was flipped from cycle to cycle. The data was gathered for two separated beam momenta $2026$ MeV/c and $2188$ MeV/c, which correspond to excess energy over the $\eta$ production threshold of $15$ MeV and $72$ MeV, respectively. More details of the analysis can be found in [26].

## 3 Search for the $\eta$-mesic nuclei

The recent reviews on the search for mesic nuclei can be found in [3, 27–33]. The WASA-at-COSY collaboration [34] performed three dedicated experiments with aim to search for the $\eta$-mesic nuclei in $^4\text{He}$ and $^3\text{He}$ systems in the deuteron-deuteron and proton-deuteron collisions, respectively [35–39]. The choice of the light nuclei was motivated by both theoretical considerations (see e.g. [40, 41]) as well as the earlier measurements by SATURNE, ANKE and COSY-11 [42–46], that provided strong experimental hints for the existence of the bound state in the $^3\text{He} - \eta$ and $^4\text{He} - \eta$ systems. The main experimental idea for the $^4\text{He}$ is based on the measurement of the excitation function of the $dd \rightarrow ^3\text{He}N\pi$ reaction for energies in the vicinity of the $\eta$ production threshold and on the selection of events with low $^3\text{He}$ center-of-mass (CM) momenta. In the case of existence of the $^4\text{He} - \eta$ bound state we expect to observe a resonance-like structure in the excitation function below the threshold for the production of the $^4\text{He} - \eta$ system. The $^3\text{He}$ state is investigated in proton on deuteron collisions. The details can be found in [47].

## 4 Summary

The latest preliminary results from the 2010 experiment in $^4\text{He} - \eta$ system, do not confirm the existence of the $\eta$-mesic nuclei. The preliminary value of the upper limit obtained from the simultaneous fit, taking into account the isospin dependence of the $dd \rightarrow (^4\text{He}-\eta)_{\text{bound}} \rightarrow ^3\text{He}n\pi^0$ and $dd \rightarrow (^4\text{He}-\eta)_{\text{bound}} \rightarrow ^3\text{He}p\pi^-$ excitation functions , of order of few nb can be compared to the theoretical estimate of 4 nb [48]. In case of the $^3\text{He} - \eta$ system, the analysis is ongoing. The current experimental upper limit for the production of $pd \rightarrow (^3\text{He}-\eta)_{\text{bound}} \rightarrow pp\pi\pi^-$ comes from the COSY-11 measurement and is equal to about 270 nb [49]. Due to the high statistics the expected sensitivity in current WASA
analysis is of order of 10 nb, which, taking into account the theoretical estimate of 80 nb [50], should be sufficient to confirm or rule out the hypothesis of existence of the $^3\text{He} - \eta$ mesic nuclei.

The WASA-at-COSY determined the analysing power in the $\bar{p}p \rightarrow pp\eta$ reaction with two order of magnitude higher precision than the previous COSY-11 measurement. The preliminary results of the angular dependency of the analysing power is in disagreement with the prediction by both the pseudo-scalar and the vector exchange models. For higher energy ($Q = 72$ MeV), the Ps-Pp interference is clearly observed.

We acknowledge support by the Polish National Science Center through grant No. 2011/03/B/ST2/01847,2011/01/B/ST2/00431, 2013/11/N/ST2/04152, by the FFE grants of the Research Center Juelich, by the EU Integrated Infrastructure Initiative HadronPhysics Project under contract number RI3-CT-2004-506078 and 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 N. 227431.

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