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Constraining the optical potential in the search for η-mesic ^{4}He

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ABSTRACT

A consistent description of the $dd \to {}^4\text{He}\eta$ and $dd \to ({}^4\text{He}\eta)_{bound} \to X$ cross sections was recently proposed with a broad range of real (V_0) and imaginary (W_0), $\eta-{}^4$He optical potential parameters leading to a good agreement with the $dd \to {}^4\text{He}\eta$ data. Here we compare the predictions of the model below the η production threshold, with the WASA-at-COSY excitation functions for the $dd \to {}^3\text{He}N\pi$ reactions to put stronger constraints on (V_0, W_0). The allowed parameter space (with $|V_0| <\sim 60$ MeV and $|W_0| <\sim 7$ MeV estimated at 90% CL) excludes most optical model predictions of $\eta-{}^4$He nuclei except for some loosely bound narrow states.

1. Introduction

Mesic nuclei are currently one of the hottest topics in nuclear and hadronic physics, both from experimental [1–5] and theoretical points of view [6–25]. This exotic nuclear matter is supposed to consist of a nucleus bound via the strong interaction with a neutral meson such as the η, η', K or ω. Although, its existence has been predicted over thirty years ago, it still remains to be one of the undiscovered nuclear objects. Some of the most promising candidates for such bound states are η-mesic nuclei, postulated by Haider and Liu in 1986 [26] following the coupled channel calculations by Bhalerao and Liu [27] which reported an attractive η-nucleon interaction. Current studies of hadron- and photon-induced production of the η meson resulting in a wide range of values of the ηN scattering length, $a_{\eta N}$, indicate the interaction between the η meson and a nucleon to be attractive and strong enough to create an η-nucleus bound system even in light nuclei [7–10,28–30]. However, experiments performed so far have not brought a clear evidence of their existence [31–38]. They provide only signals which might be interpreted as indications of the η-mesic nuclei. The interested reader can find recent reviews on the η mesic bound states searches in Refs. [4,5,14,16,39–44].

Some of the promising experiments related to η-mesic nuclei have been performed with the COSY facility [45]. The most recent of these involves the measurement of the $dd \to {}^3\text{He}n\pi^0$ and $dd \to {}^3\text{He}p\pi^-$ reactions which has been performed by the WASA-at-COSY Collaboration. Due to the lack of theoretical predictions for cross sections below the η production threshold, the data have been analyzed assuming that the signal from the bound state has a Breit–Wigner shape [1,2]. However, a better guidance for the shape of the cross sections for the $dd \to ({}^4\text{He}-\eta)_{bound} \to {}^3\text{He}N\pi$ processes is provided by a theoretical model described in Ref. [6] in the excess energy range relevant to the η-mesic nuclear search. Given that the model is the very first attempt to provide a consistent description of the data below and above the η meson production threshold, the authors used a phenomenological approach with an optical potential for the $\eta-{}^4$He interaction. The available data on the $dd \to {}^4\text{He}\ \eta$ reaction is reproduced quite well for a broad range of optical potential parameters for which the authors predict the cross section spectra corresponding to η-^{4}He bound state formation in the subthreshold region. In this article we present a comparison between this new theoretical model and experimental data collected by WASA-at-COSY in order to further constrain the range of the allowed $\eta-{}^4$He optical potential parameters. The latter, as we shall see, narrows down the search for η-mesic helium to a region of small binding energies and widths.

2. Theoretical model

The formalism presented in Ref. [6] predicted for the first time, the formation rate of the η-mesic ^{4}He in the deuteron–deuteron

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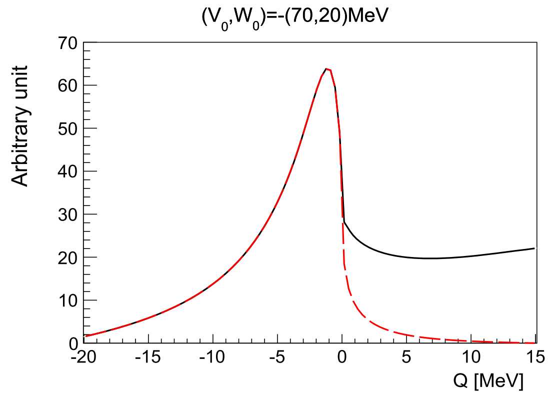

Fig. 1. Calculated total cross section of the $dd \to ({}^4\text{He}-\eta)_{bound} \to {}^3\text{He}N\pi$ reaction for the formation of the ${}^4\text{He}-\eta$ bound system plotted as function of the excess energy Q for $\eta-{}^4\text{He}$ optical potential parameters $(V_0, W_0) = -(70, 20)$ MeV. The black solid line denotes the total cross section σ, while the red dashed line denotes the conversion part σ_{conv}. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

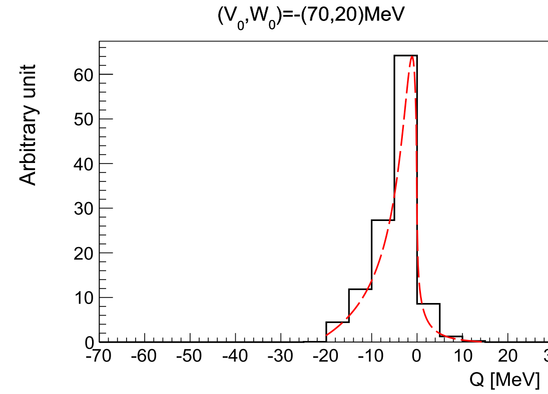

Fig. 2. Calculated conversion part of the cross section of the $dd \to ({}^4\text{He}-\eta)_{bound} \to {}^3\text{He}N\pi$ reaction for the formation of the ${}^4\text{He}-\eta$ bound system plotted as a function of the excess energy Q for $\eta-{}^4\text{He}$ optical potential parameters $(V_0, W_0) = -(70, 20)$ MeV. The cross section is scaled by fitting the escape part to the existing $dd \to {}^4\text{He}\eta$ data and the flat contribution is subtracted as well. The red dashed line shows the theoretical spectrum while the black solid line shows the spectrum after binning (details in Sec. 3).

fusion reaction within a model which reproduced the data on the $dd \to {}^4\text{He}\eta$ reaction quite well. The authors determined the total cross sections for the $dd \to ({}^4\text{He}-\eta)_{bound} \to {}^3\text{He}N\pi$ reaction based on phenomenological calculations. The calculated total cross section σ consists of two parts: conversion σ_{conv} and escape σ_{esc} part. The conversion part, determined for different parameters V_0 and W_0 of a spherical $\eta-{}^4\text{He}$ optical potential $V(r) = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_\alpha(0)}$, is equal to the total cross section in the subthreshold excess energy region where the η meson is absorbed by the nucleus (its energy is not enough to escape from the nucleus), while the η meson escape part contributes to the excess energy region above the threshold for η production and can be calculated as $\sigma_{esc} = \sigma - \sigma_{conv}$. Fig. 1 shows the example of a calculated total cross section for $\eta-{}^4\text{He}$ optical potential parameters $(V_0, W_0) = -(70, 20)$ MeV.

We should mention here that the above theoretical calculations (which are being used in the present work) were done assuming the one-nucleon absorption of the η meson since the strength of the multi-nucleon absorption processes is not well known. Based on the experimental data on the $pn \to d\eta$ and $pN \to pN\eta$ reactions, the strength of the η meson absorption by a two-nucleon pair at the nuclear center was estimated in [46] to be 4.2 MeV and 0.2 MeV for the spin triplet and singlet nucleon pairs, respectively. This strength can be larger for ^{4}He because of the higher central density as mentioned in [47]. The values of the W_0 parameters in the present work could be compared with these numbers to get a rough estimate of the ratio of the one- and two-body absorption probability at the nuclear center. The two body absorption potential is expected to provide an additional contribution to the conversion cross section. However, it is only the one-nucleon absorption cross section which should be compared with the present data since multi-nucleon absorption processes would contribute to different final states not considered in the present work. Thus, the present analysis of experimental data from Ref. [1] based on the theoretical calculation assuming the one-body absorption seems reasonable.

The spectrum has been normalized in the sense that the escape part reproduces the measured cross sections for the $dd \to {}^4\text{He}\eta$ process [48–50]. Moreover, the flat contribution in the conversion spectrum, considered to be a part of the background, has been subtracted (taking the minimum value of the σ_{conv} in the excess energy range from -20 to 15 MeV).

Since the signal from the η-mesic bound system is expected below the threshold for the η meson production, the authors focused here only on the conversion part of the cross sections. An example of the calculated σ_{conv} is shown in Fig. 2 for potential parameters $(V_0, W_0) = -(70, 20)$ MeV. The authors of Reference [6] concluded that as a next step it would be important to compare these theoretical results with the experimental data, convoluting the theoretical cross sections with the experimental resolution functions. In this article we present results of such a comparison. The details are presented in Section 4 which will be preceded by a brief description of the experimental conditions.

3. Experimental data

Recent measurements at WASA-at-COSY, dedicated to search for η-mesic ^{4}He nuclei were carried out using the unique ramped beam technique allowing for the beam momentum to be changed slowly and continuously around the η production threshold in each of the acceleration cycles [1,2,42,44]. This technique allows to reduce systematic uncertainties with respect to separate runs at fixed beam energies [2,34,51]. The ${}^4\text{He}$-η bound states were searched by studying the excitation functions for $dd \to {}^3\text{He}n\pi^0$ and $dd \to {}^3\text{He}p\pi^-$ processes in the excess energy range Q from -70 MeV to 30 MeV. The obtained excitation functions do not reveal any direct narrow structure below the η production threshold, which could be considered as a signature of the bound state. Therefore, only the upper limit of the total cross section for the η-mesic ^{4}He formation was determined.

In the first approach, the upper limits of the total cross sections for both processes were estimated at a 90% confidence level (CL) fitting simultaneously the excitation functions with a sum of a Breit–Wigner and a second order polynomial function corresponding to the bound state signal and background, respectively. Moreover, the isospin relation between $n\pi^0$ and $p\pi^-$ pairs was taken into account. The corresponding data analysis is presented in detail in Ref. [1]. The analysis resulted in the value of the upper limit in the range from 2.5 to 3.5 nb for the $dd \to ({}^4\text{He}-\eta)_{bound} \to {}^3\text{He}n\pi^0$ process and from 5 to 7 nb for the $dd \to ({}^4\text{He}-\eta)_{bound} \to {}^3\text{He}p\pi^-$ reaction. Systematic uncertainty, contributed mainly from the assumption of the Fermi momentum of the N^* resonance inside ^{4}He [13], to be equal to that of a nucleon in ^{4}He [52], varies from 42% to 46% for both reactions.

These experimental results are revisited in the next section in the light of a new theoretical model [6] which reproduces the $dd \to {}^4\text{He}\eta$ cross section data and with the same $\eta-{}^4\text{He}$ optical