η–NUCLEUS INTERACTION FROM THE $d + d$ REACTION AROUND THE η-PRODUCTION THRESHOLD*

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We have developed a theoretical model to evaluate the formation rate of the η-mesic nucleus in the $d + d$ fusion reaction and show the calculated results. We have compared our results with existing data of the $d + d \rightarrow \eta + \alpha$.

1. Introduction

Recently, the new experiments of the $d + d \rightarrow (\eta + \alpha) \rightarrow X$ reaction have been proposed and performed at WASA-at-COSY [1–7]. In the experiments, the formation cross section of the η-mesic nucleus in the α particle in the $d+d$ fusion reaction is planned to be measured by observing the emitted particles from the decay of the η-mesic nucleus below the η-production threshold. In Refs. [6, 7], the upper limits of the bound state production are reported for the $d + d \rightarrow {}^3\mathrm{He} + n + \pi^0$ and $d + d \rightarrow {}^3\mathrm{He} + p + \pi^-$ reactions. There were also the data of η-production reaction $d + d \rightarrow \eta + \alpha$ above the threshold [8–10], which are expected to provide the valuable information on the reaction mechanism.

In this paper, we show the numerical results for the formation cross section of the η bound states in the $d+d$ reaction evaluated by a theoretical model developed in Ref. [11].

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2. Brief description of the model

We have developed a theoretical model to evaluate the formation rate of the η-mesic nucleus in the fusion reactions $d+d \to \eta+\alpha$ [11]. In this model, we have calculated the cross sections of the diagram shown in Fig. 1 and obtain the contributions of the conversion part and escape part separately in addition to the total cross section by Green's function method.
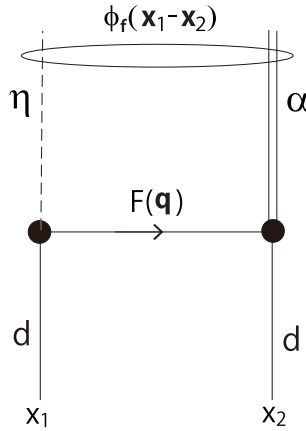

Fig. 1. The schematic diagram of the $d + d \to \eta + \alpha$ reaction.

For the numerical evalaution, we assume the η–α optical potential has the following form:

$$U_{\text{opt}}(r) = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_\alpha(0)}, \tag{1}$$

where V_0 and W_0 are the parameters to determine the potential strength at the center of the α particle. The density of the α particle, $\rho_\alpha(r)$, is assumed to have Gaussian form with the range parameter which reproduce the R.M.S radius of α to be 1.681 fm. As the practical form of the reaction form factor F, in this article we assume the Gaussian as

$$F(\vec{p}) = (2\pi)^{3/2}\left(\frac{2}{p_0^2\pi}\right)^{3/4}\exp\left[-\frac{\vec{p}^2}{p_0^2}\right], \tag{2}$$

and treat p_0 as a phenomenological parameter.

3. Numerical results

In Fig. 2, we show the calculated results for $(V_0, W_0) = -(30, 5), -(30, 20)$ and $-(30, 40)$ MeV cases with $p_0 = 500$ MeV/c. In these weak attractive potential cases with $V_0 = -30$ MeV, we find the step-like structure at the threshold for weak absorptive case with $W_0 = -5$ MeV, which again becomes less prominent for stronger absorptive potential with larger $|W_0|$ value.
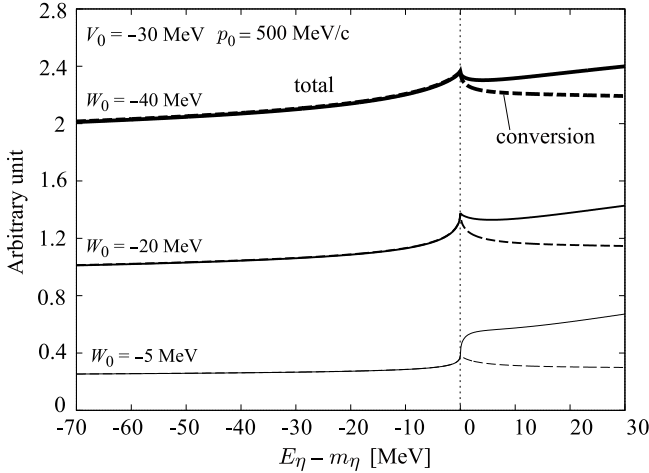

Fig. 2. Calculated cross sections of the $d + d \to (\eta + \alpha) \to X$ reaction for the formation of the η–α bound systems plotted as functions of the η excited energy $E_\eta - m_\eta$. The parameters of the η–α optical potential are $(V_0, W_0) = -(30, 5), -(30, 20)$, and $-(30, 40)$ MeV, and the p_0 parameter is fixed to be $p_0 = 500$ MeV/c. The solid lines indicate the total cross sections σ, and the dashed lines the conversion parts σ_{conv}.

In Fig. 3, we show the calculated escape parts of the spectra with experimental data for $V_0 = -30$ MeV cases with different strength of the absorptive potential. The calculated results are scaled to fit the experimental data. The agreement between calculated results and the data above the threshold seems reasonably good in these cases. As we can see from Fig. 3, the shape of the escape part is relatively insensitive to the value of the potential parameter W_0 and, in this case, it could be difficult to distinguish the potentials only from the escape part.

To compare our calculated results with the data in the subthreshold region, we need to take into account the observed final states in the actual experiments. In the experiments, since the η meson cannot be emitted in the subthreshold region, the pion, nucleon, and residual three-nucleon systems are mainly considered to be observed as the final state of the one-nucleon
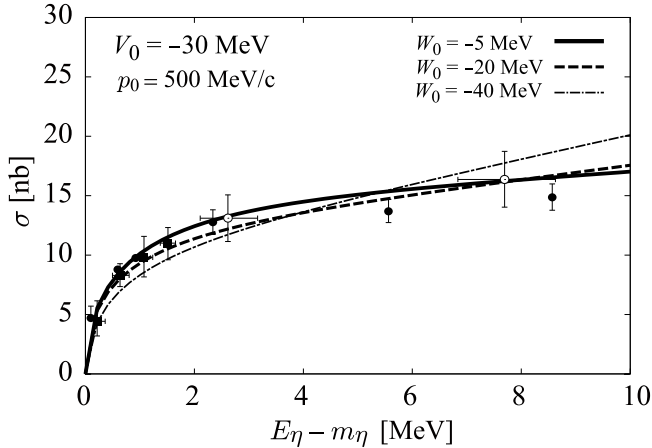
Fig. 3. Calculated escape part σ_{esc} in Fig. 2 is plotted with the experimental data of the $d + d \rightarrow \eta + \alpha$ reaction indicated by black squares [8], black circles [9], and open circles [10]. The parameters of the η–α optical potential are $(V_0, W_0) = -(30, 5), -(30, 20)$, and $-(30, 40)$ MeV and the p_0 parameter is fixed to be $p_0 = 500$ MeV/c. The line is roughly fitted to data by eye.

η-meson absorption decay of η–α bound states. Thus, we show in Fig. 4 the calculated conversion parts of the spectra which correspond to the η-absorption processes.
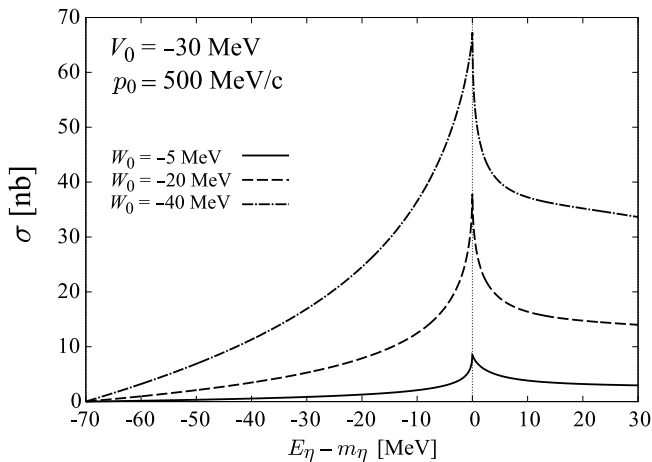

Fig. 4. Calculated conversion part of cross sections of the $d + d \rightarrow (\eta + \alpha) \rightarrow X$ reaction scaled by the same factor used in Fig. 3 plotted as functions of the η excited energy $E_\eta - m_\eta$. The flat contributions are subtracted. The parameters of the η–α optical potential are $(V_0, W_0) = -(30, 5), -(30, 20)$, and $-(30, 40)$ MeV, and the p_0 parameter is fixed to be $p_0 = 500$ MeV/c.

4. Summary

We have developed a theoretical model to evaluate the formation rate of the η–α bound states in the $d + d$ fusion reaction. Because of the difficulties due to the large momentum transfer which is unavoidable to produce η meson in the fusion reaction, we formulate the model in a phenomenological way. We have shown the numerical results for the cases with the weak attractive potential cases.

We have found that the data of η production above threshold provide important information on the absolute strength of the reaction by comparing them with the escape part of the calculated results.

The upper limit of the formation cross section of the η-mesic nucleus reported in Refs. [6, 7] also provides the important information on the strength of the η–nucleus interaction. We would like to stress here that simultaneous fit to both data of $d + d \rightarrow \eta + \alpha$ and $d + d \rightarrow (\eta + \alpha) \rightarrow X$ using our model make it possible to provide valuable information on η–nucleus interaction. The details of this work will be reported in Ref. [11].

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