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Photoproduction of η -mesons off light nuclei.

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Photoproduction of η -mesons off deuterons is studied within the Alt-Grassberger-Sandhas formalism for different parameters of the ηN interaction. The calculations revealed peaks in the energy dependence of the total cross-section.

1. INTRODUCTION

Photoproduction of η -mesons off nuclei has attracted essential interest during the last decades, experimentally and theoretically as well. Theoretical analysis of (γ, η) -reactions on nuclei is hampered by the three major problems: the unknown off-shell behavior of the two-body $\gamma N \rightarrow \eta N$ amplitude, inaccuracies in the description of the nuclear target as a many-body system, and rescattering effects in the final state. The simplest reaction is, of course, the process of coherent η photoproduction on deuteron. There are many theoretical studies devoted to (γ, η) reactions on deuteron. Early attempts to go beyond a simple impulse approximation led to very different conclusions [1] – [3] as do more recent approaches based on the effective two-body formulations [4], [5]. Moreover, the experimental cross-section [6] of the reaction

$$\gamma + d \rightarrow \eta + d \tag{1}$$

in the near-threshold region is far above these theoretical predictions. Therefore, a reliable description of η photoproduction on deuteron is needed.

2. FORMALISM

To consider reaction (1), we employ the exact Alt-Grassberger-Sandhas (AGS) formalism modified to include the electromagnetic interaction. The advantage of working with coupled equations involving the elastic and rearrangement operators of the final state, is not only suggested by questions of uniqueness, but also by the relevance of rescattering effects which were found to give a significant contribution to the corresponding amplitude [7]. In the operator form, the AGS equations for the ηd system read

$$U_{11}(z) = T_2(z)G_0(z)U_{21}(z) + T_3(z)G_0(z)U_{31}(z),$$

$$\begin{aligned} U_{21}(z) &= G_0^{-1}(z) + T_1(z)G_0(z)U_{11}(z) + T_3(z)G_0(z)U_{31}(z), \\ U_{31}(z) &= G_0^{-1}(z) + T_1(z)G_0(z)U_{11}(z) + T_2(z)G_0(z)U_{21}(z), \end{aligned} \quad (2)$$

with $G_0(z)$ being the Green's operator of the three particles involved, operator $T_\alpha(z) = t_\alpha(z - \mathbf{q}_\alpha^2/2M_\alpha)$ is a two-body operator embedded in the three-body space; $t_1 = t_{NN}$, $t_2, t_3 = t_{\eta N}$, and operators $U_{ij}, i, j = 1, 2, 3$ describe elastic scattering and rearrangement processes (for more details see, for example, Ref. [9]).

A photon can be introduced into this formalism by considering the ηN and γN states as two different channels of the same system. This means that we should replace the T-operator $t_{\eta N}$ by a 2×2 matrix. It is clear, that such replacements of the kernels of integral equations (2) lead to the corresponding solutions having a similar matrix form

$$t_{\eta N} \rightarrow \begin{pmatrix} t^{\gamma\gamma} & t^{\gamma\eta} \\ t^{\eta\gamma} & t^{\eta\eta} \end{pmatrix} \quad U_{\alpha\beta} \rightarrow \begin{pmatrix} W_{\alpha\beta}^{\gamma\gamma} & W_{\alpha\beta}^{\gamma\eta} \\ W_{\alpha\beta}^{\eta\gamma} & W_{\alpha\beta}^{\eta\eta} \end{pmatrix}. \quad (3)$$

Here $t^{\gamma\gamma}$ describes the Compton scattering, $t^{\eta\gamma}$ the photoproduction process, and $t^{\eta\eta}$ the elastic ηN scattering.

It is technically more convenient to consider the reaction of η -photoabsorption, which is the inverse of reaction (1). Then the photoproduction cross-section can be obtained by applying the detailed balance principle. Therefore, we need the amplitude $W_{11}^{\eta\eta}$ which in the first order of electromagnetic interaction can be written in the form

$$W_{11}^{\eta\eta} \approx T_2^{\eta\eta} G_0(z) W_{21}^{\eta\eta} + T_3^{\eta\eta} G_0(z) W_{31}^{\eta\eta}. \quad (4)$$

It should be emphasized that via the operators $W_{21}^{\eta\eta}$ and $W_{31}^{\eta\eta}$ in (4) all the rescattering effects are properly taken into account. The corresponding transition amplitudes obey the system (2) which is reduced further to two coupled equations because of identity of the nucleons (see Ref. [8]). It is customary to reduce the dimension of these equations by representing the two-body T-operators in separable form.

The S-wave nucleon-nucleon separable potential is adopted from Ref. [10] with its parameters slightly modified to be consistent with more recent NN data (see Ref. [8]). The η -nucleon T-matrix is taken in the form

$$t_{\eta N}(p', p; z) = (p'^2 + \alpha^2)^{-1} \frac{\lambda}{(z - E_0 + i\Gamma/2)} (p^2 + \alpha^2)^{-1}. \quad (5)$$

The range parameter $\alpha = 3.316 \text{ fm}^{-1}$ was determined in Ref. [11], while E_0 and Γ are the parameters of the S_{11} resonance [12]. The strength parameter λ is chosen to reproduce the η -nucleon complex scattering length $a_{\eta N}$. The value of $a_{\eta N}$ is not accurately known, different analysis provided for it values in the range $0.27 \text{ fm} \leq \text{Re } a_{\eta N} \leq 0.98 \text{ fm}$, $0.19 \text{ fm} \leq \text{Im } a_{\eta N} \leq 0.37 \text{ fm}$. Recently, however, most of the authors agreed that $\text{Im } a_{\eta N}$ is around 0.3 fm.

To construct a separable T-matrix of the reaction $\eta N \rightarrow \gamma N$, we used the results of Ref. [13] where $t^{\eta\gamma}$ (which is equal to $t^{\gamma\eta}$) was obtained as an element of a multi-channel T-matrix on the energy shell. For our calculations, we extended this T-matrix off the energy shell, using the Yamaguchi form-factors which become unit on the energy shell. It is generally believed that $t^{\eta\gamma}$ is different for neutrons and protons. We assumed that they have the same functional form and differ by a constant factor $t_n^{\eta\gamma} = A t_p^{\eta\gamma}$. A multipole analysis gives for this factor the following estimate [14]: $A = -0.84 \pm 0.15$.

3. RESULTS

As was expected, our calculations revealed a very strong final state interaction in the reaction (1). A comparison of the corresponding cross-sections obtained by solving the AGS equations and by using the Impulse Approximation (IA) is given in Fig. 1, where the IA-results are multiplied by 10. Besides the fact that the IA-curve is generally an order of magnitude lower, it does not show a resonant enhancement which is clearly seen when all the rescattering and re-arrangement processes are taken into account. In this connection, it should be noted that experimental data [6] for the reaction (1), given in Figs. 2 and 3 show a pronounced enhancement of the differential cross-section at low energies.

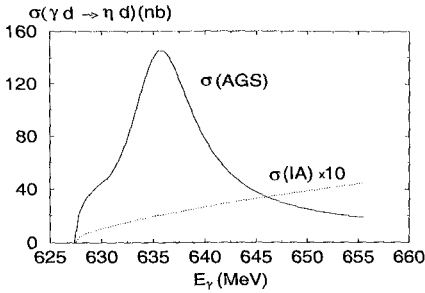


Figure 1. Total cross-section, calculated within a rigorous few-body theory (AGS) and Impulse Approximation (IA).

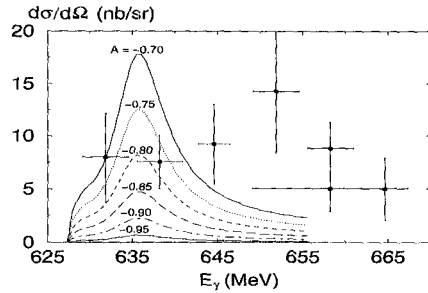


Figure 2. Differential cross-section ($\Theta_{\eta}^{cm} = 90^\circ$), calculated with different choices of the ratio A .

In order to examine the dependence of our calculations on the choice of the parameters of the T-matrices t^m and t^n , we did variations of $A = t_n^m/t_p^m$ and $\text{Re } a_{\eta N}$ within the corresponding uncertainty intervals. One of the most important parameters of the theory is the ratio of the photoproduction amplitudes for neutron and proton (A). Six curves corresponding to different choices of A are depicted in Fig. 2. These curves were calculated with $a_{\eta N} = (0.75 + i0.30)$ fm. The experimental data are taken from Ref. [6].

In Fig. 3, we present the result of our calculations for five different choices of $\text{Re } a_{\eta N}$, namely, 0.55 fm, 0.65 fm, 0.725 fm, 0.75 fm, and 0.85 fm. This sequence of $\text{Re } a_{\eta N}$ corresponds to the upward sequence of the curves in the near-threshold region. The parameter A was taken to be -0.75 . A comparison of the curves depicted in Figs. 2 and 3 with the corresponding experimental data shows that no agreement with the data can be reached unless the ratio A is greater than -0.80 .

Under all variations of the parameters, however, the resonant peak remains about 15 MeV to the left of the experimental peak. Since this peak is due to the resonant final state interaction between the η meson and deuteron, we may expect that it can be shifted to the right by introducing a repulsion into the ηN interaction. To introduce an ηN repulsion which preserves the separable form of the corresponding T-matrix, we used the method

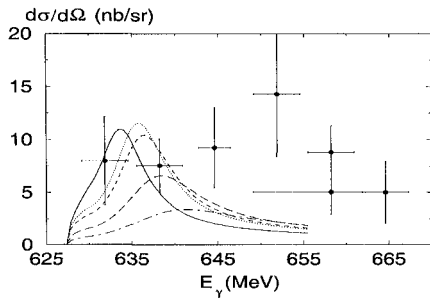


Figure 3. Differential cross-section ($\Theta_{\eta}^{cm} = 90^{\circ}$) with different choices of $\text{Re } a_{\eta N}$.

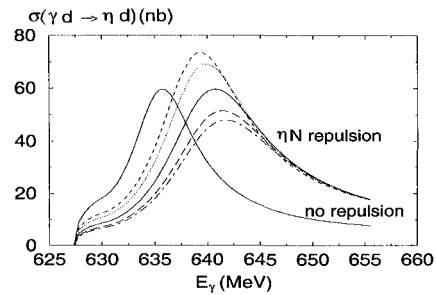


Figure 4. Shift of the resonant peak of the total cross-section due to the ηN repulsion.

suggested in Ref. [10] where a separable nucleon-nucleon T-matrix includes an energy dependent factor, $b(E) = -\tanh(1 - E/E_c)$. This factor causes the NN phase-shift to change sign at the energy $E_c = 0.816 \text{ fm}^{-1}$, which is equivalent to presence of an NN repulsion. Since the purpose of our numerical experiment was to check if an ηN repulsion could shift the peak to the right and there is no information about such repulsion, we used the same function $b(E)$ and did variations of E_c , namely $E_c/3$, $E_c/2$, E_c , $2E_c$, and $3E_c$. The corresponding curves are shown in Fig. 4 where the larger E_c the lower is the curve. Parameters used here are: $a_{\eta N} = (0.75 + i0.30) \text{ fm}$ and $A = -0.85$.

Therefore, comparison of our calculations with the experimental data suggests that $A > -0.80$, $\text{Re } a_{\eta N} > 0.75 \text{ fm}$, and that the ηN interaction is likely to be repulsive at short distances.

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