Final state interaction effects in $\eta$ photoproduction on two- and three-body nuclei

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The role of final state interaction in $\eta$ photoproduction on a deuteron as well as on three-body nuclei is investigated within few-body scattering theory. Deviation of the theory from the available experimental results is briefly discussed.

1. Incoherent $\eta$ photoproduction on a deuteron

Photoproduction of $\eta$ mesons on the deuteron near threshold is strongly influenced by final state interaction (FSI). The main reason for the importance of FSI is a strong mismatch between a large momentum transfer and a minimal kinetic energy in the final $\eta NN$ system, which on the other hand can effectively be balanced by the interaction between the final particles. Furthermore, an appreciable attraction in the $\eta NN$ system generates a virtual pole in the three-body scattering amplitude [1], which in turn leads to a strong rise of the cross section just above threshold in agreement with experimental results [2].

The calculation was performed using a separable representation of the driving $\eta N$ and $NN$ scattering amplitudes as described in detail in [1]. For the $\eta N$ interaction an isobar ansatz of [3] was used with inclusion of $S_{11}(1535)$ only. The corresponding parameters were adjusted such that the $\eta N$ scattering length $a_{\eta N} = (0.5 + i0.32)$ fm, which we consider as an approximate average of the scattering lengths provided by modern $\eta N$ analyses, is reproduced and that at the same time a good description is provided of the processes $\pi N \rightarrow \pi N$, $\pi^- p \rightarrow \eta n$, and $\pi N \rightarrow \pi\pi N$. The $NN$-interaction was considered only in the dominant $s$ wave scattering states. We have used the version BEST3 for $^1S_0$ and correspondingly BEST4 for the triplet states. The separable representation allows one to reduce the three-body problem to a set of integral equation in one variable only, whose structure is analogous to the usual Lippmann-Schwinger equation for two coupled channels ($\eta + d$) and $(N + N^*)$.

The resulting inclusive cross section for $\gamma d \rightarrow \eta X$ ($X = \{np, d\}$) is shown by the solid curve in Fig.1. As one can see, although the three-body calculation leads to a sizeable improvement as compared to the impulse approximation (dashed line), a quantitative agreement with the data is not yet achieved. A possible reason for this disagreement could be the neglect of $\pi N N$ configurations in the calculation. The contribution of the
intermediate pions depends strongly on the role of large momentum transfers in the reaction, since it is associated with a large intermediate momentum and consequently is effective only at short distances. For example, inclusion of $\pi NN$ configurations provides only a small fraction of the $\eta d$ scattering cross section \cite{1}. At the same time they contribute rather sizeably to coherent $\eta$ photoproduction on the deuteron \cite{4}, where the large transferred momenta emphasize naturally the short distances in the target. In view of the systematic deviation between theory and the data, the role of intermediate pions in the incoherent channel $\gamma d \rightarrow \eta np$ must be considered in greater detail.

2. Coherent $\eta$ photoproduction on $^3$He

The study of $\eta^3$He elastic scattering, based on four-body Faddeev-Yakubovsky theory \cite{5}, shows that there is a virtual state in this system, which in turn strongly influences low-energy $\eta$ production on three-body nuclei. This feature is demonstrated in Fig.\ref{fig:2}, where one can see a very rapid rise of the total cross section $^3$He($\gamma, \eta)^3$He, in contrast to a much flatter form predicted by the plane wave approximation (dashed line).

Comparing our results with the not yet published TAPS data \cite{6} we find a strong discrepancy. It is rather surprising that even the form of the experimental cross section is not reproduced. According to the Migdal-Watson theory \cite{7} the energy dependence of the cross section very close to threshold is determined primarily by the low-energy parameters of $\eta^3$He scattering and is therefore more or less universal for different entrance channels. For instance, as is demonstrated in Fig.\ref{fig:3} the energy dependence of the squared amplitude calculated for the reaction $^3$He($\gamma, \eta)^3$He section agrees quite well with the one extracted from the data of $d(p, \eta)^3$He \cite{8}. From this viewpoint the TAPS data could be explained only by assuming another long-range mechanism of $\eta$ production which does

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1}
\caption{Total cross section for $\gamma d \rightarrow \eta X$ (solid line). The dash-dotted (dashed) curve is obtained for the reaction $\gamma d \rightarrow \eta np$ with (without) FSI. The data are from \cite{2}.}
\end{figure}
not contribute to the reaction $d(p, \eta)^3\text{He}$.

![Figure 2. Total cross section for the photoproduction of $\eta$ on $^3\text{He}$. Solid (dashed) curve presents the result with (without) FSI.](image)

![Figure 3. Production amplitude squared for the reaction $^3\text{He}(\gamma, \eta)^3\text{He}$ compared with the experimental results for $d(p, \eta)^3\text{He}$ [8]. The theoretical result is arbitrarily normalized to the data at $p = 0.25 \text{ fm}^{-1}$.](image)

In summary, the three-body aspects of FSI are very important for $\eta$ production on light nuclei near threshold. The results of an exact three-body treatment exhibit a systematic deviation from the data. We suspect that a possible reason of this disagreement might be a pion rescattering mechanism, whose role up to now has not been investigated in detail. In the coherent reaction on $^3\text{He}$ the FSI effect is also of fundamental importance. The energy dependence of the cross section, which is determined by the low-energy parameters of $\eta^3\text{He}$ elastic scattering agrees reasonably well with that observed in the $pd$ collision. On the other hand the very strong energy dependence of the experimental cross section for $^3\text{He}(\gamma, \eta)^3\text{He}$ is not explained. We think, that this disagreement requires further investigations on the theoretical as well as on the experimental side.

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