Meson Photoproduction on light Nuclei

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Abstract. The photoproduction of mesons on light nuclei was studied intensively with the calorimeter TAPS at the tagged photon facility of the Mainzer Microtron MAMI. Threshold enhancements for \( \eta \) production on light nuclei are summarized. Furthermore, the evidence of \( \eta \)-mesic \(^3\)He is discussed.

INTRODUCTION

The study of the interaction of mesons with nucleons and nuclei is important for the understanding of the strong force. The pion-nucleon interaction at small pion momenta is weak, therefore pion-nucleus bound states do not exist. However, the \( \eta \)-N interaction at small momenta is strongly influenced by the existence of the s-wave nucleon resonance \( S_{11}(1535) \) [1]. In case of pions and kaons secondary beams can be prepared which allow a detailed study of their interaction, whereas the \( \eta \) interaction with other hadrons can only be investigated indirectly. One way is to produce the \( \eta \) with some incident beam and study the subsequent final state interaction with the target nucleus or nucleon.

The \( \eta \) meson has attracted much interest, since the existence of bound \( \eta \)-nucleus systems has been discussed for a long time. An attractive s-wave interaction was already found in the coupled channel analysis of \( \eta \) production by Bhalerao and Liu [2]. Only shortly after that, the first suggestion of bound \( \eta \)-nucleus systems with \( A > 10 \) termed \( \eta \)-mesic nuclei was introduced by Liu and Haider [3]. However, although it was searched in different reactions for such states, up to recently no conclusive evidence was reported.

RE-SCATTERING EFFECTS IN MESON - LIGHT NUCLEI SYSTEMS

The investigation of \( \eta \) production reaction on light nuclei in the threshold region is a very useful tool for the study of \( \eta \)-nucleus interactions. Any significant final state interaction (FSI) of the \( \eta \)-meson with the nucleus, in particular the formation of (quasi)bound states in the vicinity of the production threshold, will give rise to an enhancement of the cross section relatively to the expectation for phase space behavior. Such deviation can also arise from FSI effects between the nucleons. Consequently, for the interpretation of these results reliable model calculations are needed which account for these trivial effects.

\( \eta \) photoproduction on deuterium has been measured with the TAPS detector at the Mainzer microtron MAMI. The total cross section for the inclusive \( \eta \) production channel...
is shown in Fig. 1. A very good agreement between the impulse approximation and the measured cross section is found for higher incident beam energies (compare inset in Fig. 1). In contrast, the data close to threshold shows a very strong enhancement indicating the importance of FSI. This effect was explained by Sibirtsev and others in the Juelich meson baryon model by a calculation which described the reaction within an isobar model. The FSI of the \( \eta N \) and the NN systems was derived from a meson exchange model. A constructive interference of the \( \eta N \) and NN FSI was claimed to be responsible for the strong threshold effect [4]. Recently Fix and Arenhoevel have recalculated the \( \gamma d \rightarrow \eta np \) channel using a realistic NN potential (Bonn potential) and a three body formalism [5]. The results for the IA and the FSI of the Juelich model could not be reproduced. The calculated cross section at threshold, which includes the coherent \( \eta \) production on deuterium to describe the inclusive \( \eta \) photoproduction, slightly underestimates the measured data. As a summary, the discrepancies in the theoretical descriptions and in the interpretations of the nature of the FSI effects are still not fully understood. Additionally, inclusive \( \eta \)-photoproduction on \( ^4 \text{He} \) was measured and qualitatively the cross section shows a comparable enhancement at threshold [6], but theoretical descriptions are much more demanding for this case.

Recently, another interesting effect of \( \eta \) FSI has been pointed out in a preliminary data set measured with CLAS at Jefferson Lab [7]. The excitation function for coherent \( \pi^0 \) photoproduction on deuterium is shown in Fig. 2 as a function of the center of mass polar angle of the \( \pi^0 \) meson. These data show at backward angles an enhancement right at the threshold of \( \eta \) production off the free nucleon (707 MeV). This effect has been interpreted as a primary production of a \( \eta \) meson which subsequently re-scatters on the other nucleon producing a \( \pi^0 \) meson [8].
EVIDENCE FOR $\eta$-MESIC NUCLEI

The interaction of $\eta$ mesons with nuclei has been extensively discussed in the past. The first time, Liu and Haider suggested bound $\eta$-nucleus systems termed $\eta$-mesic nuclei for $A>10$ [3]. However, although it was searched in different reactions for such states, no conclusive evidence was reported. Recently, Sokol and others claimed the formation of $\eta$-mesic nuclei with mass number $A=11$ in the $\gamma^{12}C$ reaction with the decay chain: $\gamma+A\rightarrow N_1+(A-1)\eta\rightarrow N_1+(N_2+\pi)+(A-2)$.

More recent analysis of the $\eta N$ scattering length found large values of its real part.

FIGURE 2. Preliminary excitation function for coherent $\pi^0$ photoproduction [7] as a function of the center of mass $\pi^0$ polar angle. The $\eta$ photoproduction threshold on the free nucleon is at 707 MeV.

FIGURE 3. Squared amplitudes for the proton [9, 10] and photon [11] induced $\eta$ production on $^3$He arbitrary normalized. The solid curve shows an optical model fit to the near threshold data [10].
which span the range from 0.2 - 1.0 and most cluster between 0.5 - 0.8 (compare for an overview [4]). As a result, speculations about the existence of light \( \eta \)-mesic nuclei raised. \( \eta \) production near threshold was intensively investigated in the reactions: \( pp \rightarrow pp\eta, np \rightarrow d\eta, pd \rightarrow \eta^3\text{He}, \bar{d}d \rightarrow \eta^4\text{He}, pd \rightarrow pd\eta \). All reactions showed more or less pronounced threshold enhancements. If \( \eta \) bound states do exist, they should show up independently of the initial state of the reaction. Alternatively, photoproduction of \( \eta \)-mesons from light nuclei is a clean tool for the preparation of the \( \eta \)-nucleus final state with small relative momenta. Photoproduction of \( \eta \) mesons has been investigated in detail, in particular with TAPS at MAMI and again, threshold enhancements were observed as exemplary discussed in the previous section. Furthermore, these experiments clearly demonstrated that the reaction is dominated by an iso-vector, spin-flip amplitude [12]. Consequently the \( I = J = \frac{1}{2} \) nuclei \( ^3\text{He} \) and \( ^3\text{H} \) are the only light nuclei, where non-negligible contributions from coherent \( \eta \)-photoproduction can be expected. The coherent reaction is ideally suited for the search of near-threshold quasi-bound states and was clearly identified for \( ^3\text{He} \) [11] and after reduction of the different phase space factors, it shows a threshold behavior which is very similar to the \( pd \rightarrow \eta^3\text{He} \) reaction (compare Fig. 3).

The cross section of the coherent \( \eta \) photoproduction from \( ^3\text{He} \) [11] is depicted in Fig. 4 and compared to various model calculations [13, 14, 15]. The threshold behavior exhibits a remarkable peak-like structure, since it starts with a rather high cross section which falls down before it rises ca. 30 MeV above threshold again. Furthermore, the
isotropic angular distribution in the vicinity of the threshold which does not follow the behavior expected from the $^3$He form factor $d\sigma/d\Omega \sim F_2^2(q^2)$. Both could be indications for a quasi-bound state.

When an $\eta$-mesic nucleus is formed, it can not only decay into the coherent $\eta$ channel, but alternatively the $\eta$ meson might be absorbed on a nucleon which is excited into the $S_{11}(1535)$ resonance. In the latter case, the $S_{11}(1535)$ resonance can subsequently decay not only via $\eta$ but via pion emission as well ($\text{br} \approx 50\%$, compare Fig. 5). When the $\eta$-mesic state is populated at incident photon energies below the coherent $\eta$ threshold this is the only possible decay mode of the system. At energies above the coherent $\eta$ threshold this channel competes with the emission of $\eta$ mesons. The signature of this decay channel are pion–nucleon pairs which are emitted back-to-back in the rest frame of the $\eta$-mesic nucleus ($\gamma - ^3\text{He}$ system).

Such pion–nucleon pairs have been searched for in the channel $\pi^0 - p$, which is best suited for the TAPS calorimeter. Their excitation function [11] is shown in Fig. 6. It is dominated by the quasi-free production of a $\pi^0$ meson from the $^3$He nucleus which is visible from the strong $\Delta(1232)$ signal. This channel as well as other $\pi^0$ sources are a background channel for searched back-to-back $\pi^0 - p$ signal. The background has been taken into account by comparison of the yield for back-to-back production (opening angles larger than $170^\circ$) to the yield at opening angles of $150-170^\circ$. The back-to-back emission shows a structure at production threshold for $\eta$ mesons ($600$ MeV), which is particularly visible in the difference of the two excitation functions (compare Fig. 6, right hand side).

**FIGURE 6.** Left and center: excitation functions for the $\pi^0 - p$ final state. Opening angles in the $\gamma - ^3\text{He}$ system are depicted by triangles between $170 - 180^\circ$ and by circles between $150 - 170^\circ$. Right: difference of both opening angle ranges fitted with a Breit-Wigner curve.
The possible decay channels of $\eta - ^3\text{He}$ state into coherent $\eta$ channel (left) and into a back-to-back $\pi N$ pair (right, background subtracted). The curve indicates the best common fit.

The observed peak-like structure in coherent $\eta$ production and the signature in the excitation functions of pion-nucleon emission have been analyzed if they were consistent with the hypothesis that both are different decay channels of an $\eta$-mesic nucleus [11]. The $\eta$-mesic (quasi)bound state was parameterized with a Breit-Wigner function at position $W$ and width $\Gamma$. Proper phase space factors and the energy dependent branching ratio of the $S_{11}(1535)$ resonance have been taken into account. The result of this simplified ansatz is shown in Fig. 7. A consistent description of the cross sections for both decay channels is possible for the position of the Breit-Wigner of $W = (1481 \pm 4) \text{ MeV}$ and a width of $\Gamma = (25 \pm 6) \text{ MeV}$. This corresponds to a (quasi)bound state of a width of $\approx (25 \pm 6) \text{ MeV}$ and a binding energy of $(4 \pm 4) \text{ MeV}$. However, the statistical significance of the signal is still low ($3.5 \sigma$ for the peak in the $\pi^0 p$ channel). Furthermore, Sibirtsev and others [16] and Hanhard [17] have pointed out that a more detailed analysis of the data does not yet give solid evidence for a bound state. However, the analysis of Hanhard suggests that a precise measurement of the width of the peak structure can distinguish between a bound and virtual state. To solve this question a new experiment with TAPS and the Crystal Ball at MAMI is in preparation [18]. It aims at an improvement of the statistical precision by more than an order of magnitude.

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