# Break-up and Coherent Photoproduction of $\eta$ Mesons on the Deuteron

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We present new break-up and coherent data for $\eta$ meson photoproduction on the deuteron, using a deuterium target and tagged bremsstrahlung photons up to 1 GeV. The differential cross sections for the coherent process were measured from threshold to 800 MeV. They are much smaller than those previously reported. The break-up channel provides a direct measurement of the neutron to proton differential cross section ratios. At the $S_{11}(1535)$ resonance peak, $\sigma_n/\sigma_p = 0.68 \pm 0.06$ leading to an isoscalar to isovector amplitude ratio of $A_s/A_v = 0.096 \pm 0.02$. [S0031-9007(97)03324-3]

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The photoproduction of pseudoscalar mesons on the nucleon is a fundamental elementary process of hadronic physics. Although the experimental database for the $\pi$ meson is quite extensive [1], that for the $\eta$ meson is quite sparse. Until recently only a few differential cross section data [2] and four polarization points [3] existed and these data were obtained using untagged photon beams. Recently published measurements have studied the threshold behavior [4] and photoproduction at energies above the $S_{11}(1535)$ region [5].

Below 2 GeV, the photoproduction process is dominated by the excitation of baryonic resonances. The $\eta$ meson, having isospin $I = 0$, selects only isospin $\frac{1}{2}N^*$ resonances. Furthermore, there are only a few of these resonances which have a significant decay mode to the $\eta$-$N$ channel. The $S_{11}(1535)$ has a branching ratio to $\eta N$ much larger than the other neighboring resonances and dominates the $\eta$ meson photoproduction process below 1 GeV [6]. For $N^*$ resonances coupled to $\eta N$, in particular the $S_{11}(1535)$, the coupling strengths, expressed by the helicity amplitudes, could be extracted reliably from the $\eta$ photoproduction data, provided a complete enough database is available. The authors of Refs. [5] and [7] were the first to attempt the determination of the $S_{11}(1535)$ coupling strengths from the limited amount of $\eta$ photoproduction data available.

For the excitation of isospin $1/2$ resonances, both isospin components of the photon $I = 0$ (isoscalar) and $I = 1$ (isovector) can contribute. Accordingly the amplitude splits in two terms $A_s$ and $A_v$ for the isoscalar and isovector excitations, respectively. The separation of those components requires measurements on the proton and on the neutron. For an $\eta$-$N$ final state one can write

$$A_p(\gamma p \rightarrow p\eta) = A_s + A_v\,, \tag{1a}$$

$$A_n(\gamma n \rightarrow n\eta) = A_s - A_v\,. \tag{1b}$$

The present Letter presents a measurement of the $\eta$ meson photoproduction process on the neutron. Since there is no free neutron target, a deuterium target has been used. We have also measured the photoproduction differential cross sections on the proton. Those data will be published in a forthcoming paper [8]. In studying the $\eta$ meson photoproduction using a deuterium target, we have followed two complementary approaches. First, in the break-up channel, we detected in the final state the $\eta$ and one of the outgoing nucleons. The data show that we catch the nucleon on which the elementary reaction took place while the undetected nucleon behaved as a "spectator." For the outgoing protons or neutrons, the corresponding counting rate ratios are related to the relevant "free" nucleon cross section ratios: $\sigma_n/\sigma_p$. Those ratios are related to $A_n/A_p$ as defined in Eq. (1), and provide a connection to $A_s$ and $A_v$. Second, since the target deuteron is an isoscalar object, the coherent reaction $(\gamma d \rightarrow \eta d)$ proceeds through $A_s$. The major breakthrough of the present work is to provide the first clean identification of the coherent $\eta d$ final state, allowing us to derive the corresponding differential cross sections.

Previous experimental investigations concerning the incoherent photoproduction of $\eta$ on deuterium were limited to inclusive measurements looking at the outgoing $\eta$ [9,10]. Such measurements require a model for the reaction mechanism in order to extract the ratios $\sigma_n/\sigma_p$. The authors of Ref. [10] find approximately equal cross sections on protons and neutrons, while the more recent results [9] lead to a constant ratio of $2/3$, consistent with the values reported in the present Letter.

For the coherent production, early reported results [11] found large coherent cross sections, suggesting that the photoproduction of $\eta$ mesons could be mainly an isoscalar process. However, recent experimental investigations [9,12] provide only upper limits, 3 times smaller than the results of Ref. [11]. We found small cross sections for the coherent process. In connection with the ratios $\sigma_n/\sigma_p$, they lead to a ratio $A_s/A_v$ of the order of 10% close to the value expected from the $S_{11}(1535)$ photon couplings extracted from pion photoproduction data [13] and consistent with quark model predictions [14].

All of our measurements have used the PHOENICS [15] tagged bremsstrahlung photon beam up to 1.2 GeV at the electron stretcher ring ELSA in Bonn [16] as well as the neutral meson spectrometer SPES0 [17] to detect the $2\gamma$ and $3\pi^0$ $\eta$-decay channels. The recoil baryons were identified using the large scintillator detector systems of the standard PHOENICS detectors [18] for neutrons and charged hadrons and the SENECA neutron detector array [19] for increased neutron detection efficiency at forward angles. To increase the system efficiency for coherent deuteron detection, the AMADEUS detector [20] was also used in separate runs. All neutron detectors were located behind anticoincidence scintillator slabs. The basic idea of this system is to identify simultaneously the $\eta$ in SPES0 by its invariant mass and the energetic outgoing baryon ($p$, $n$, or $d$) in the forward scintillators by time of flight and energy loss. In principle, the measurement is exclusive, even in the case of the deuteron breakup, since the kinematical variables of the $\eta$ and one of the outgoing nucleons are experimentally determined. Therefore, for the data sample recorded with SENECA, a procedure making use of the $\chi^2$ distribution resulting from a two body kinematic fit to the experimental parameters of each event has been used. This method selects in a systematic way the $2\gamma$ decay channel (40% branch) of the $\eta$ to separate the good events (close to a two body pattern) from the background. However, due to the $4\pi$ geometry of the SPES0, the $3\pi^0$ decay channel (32% branch) of the $\eta$ has a larger efficiency than the $2\gamma$ channel. Since the granularity of the SPES0 is too coarse to resolve $6\gamma$'s, these events spoil the $\eta$ resolution and produce invariant masses significantly lower than 547.45 MeV. To preserve the statistics, in particular, for the coherent deuteron events, we have kept all the $\eta$ decay channels in the analysis of the PHOENICS events. Therefore, the missing mass is the relevant signal to identify the process, while the invariant mass serves as an $\eta$ filter. For the data sample recorded with AMADEUS, the efficiency of the system was increased even more by triggering on single $\gamma$'s in the SPES0, relying on the particular properties of the deuteron detection to cleanly identify the $\eta d$ final states.

The experiment was able to identify completely the final states corresponding to the production of an $\eta$ meson on a proton, a neutron, and the coherent deuteron. Figure 1 shows an example of the corresponding peaks for the $\eta$ missing masses, which are computed from the angle and the linear momentum of the recoil baryon assuming a two body reaction. The $\eta$ is easily identified by the missing mass in the coherent deuteron reaction as in our previous measurements on a free proton target [21]. The broadening and shift of the $\eta$ peak observed for protons and neutrons is well reproduced by a spectator model Monte Carlo simulation taking into account the characteristics of the detection system and the Fermi momentum of the struck nucleon [22]. This allows us to treat the process as a quasifree reaction and to obtain the counting rates for proton and neutron from the integration under the missing mass signal using the same criteria for cuts and background subtraction in the proton and the neutron cases. Details of the experimental setup and the analysis procedure will be reported in further

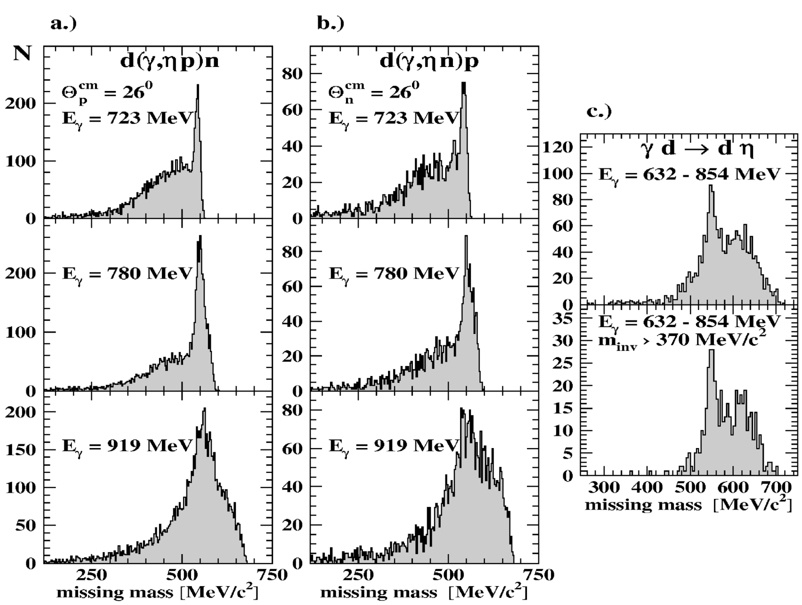


FIG. 1. The $\eta$ missing mass spectra corresponding to $\eta p$ (a), $\eta n$, (b), and $\eta d$ (c) final states detection. The peaks correspond to the $\eta$ missing mass, assuming for (a) and (b) a quasifree two body kinematics.

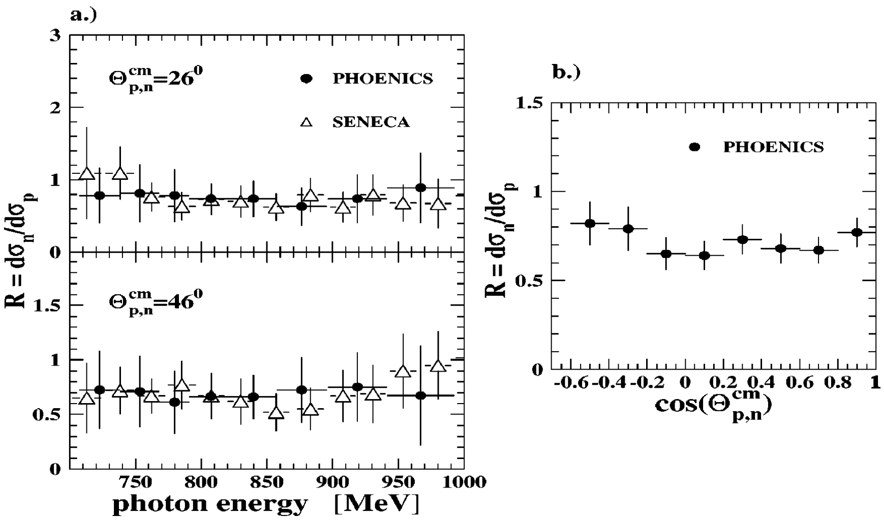


FIG. 2. Ratios $R = d(\gamma, \eta \times n)p/d(\gamma, \eta p)n$ of the cross sections corresponding to the "quasifree" reactions, as a function of incident photon energies. (b) Angular dependence of the ratio $R$. The corresponding differential cross sections have been integrated from 720 to 860 MeV. The error bars take into account statistical and systematical uncertainties.

publications. In our approach, protons and neutrons are detected in the same kinematical conditions by the same detectors. The only difference comes from the efficiency for the neutron detection (≈35%), which reduces the corresponding counting statistics accordingly.

The present experimental analysis leading to the $\sigma_n/\sigma_p$ ratios corresponds to the assumption of a pure "impulse approximation" reaction mechanism. This is justified because rescattering contributions in the break-up process were estimated to amount only to a few percent [23] and are identical for the neutron and the proton data, if "charge symmetry" holds. Therefore, they tend to compensate in the ratios and the points displayed in Fig. 2 are governed by the "free nucleon" cross section within a few percent, while the experimental error bars are larger than 10%. The free production angle corresponds to the nucleon angle and is taken in the c.m. frame of the incident photon and the struck nucleon as if the latter had been at rest, using the energy of the incident $\gamma$ and the angle of the detected nucleon in the laboratory. The $\sigma_n/\sigma_p$ ratios do not depend very much on energy, but there is a marked angular dependence. For the neutron the $\eta$ is more forward peaked. In the energy region between 720 and 860 MeV where the $S_{11}(1535)$ peaks, the average value of the experimental ratios is 0.68 ± 0.06.

An important goal of the present experimental effort is to determine the real photon coupling of the $S_{11}(1535)$ resonance to the neutron. As shown in Ref. [9], this coupling is roughly equal to the proton value multiplied by $\sqrt{\sigma_n/\sigma_p}$. However, resonances other than the $S_{11}(1535)$ can contribute. Furthermore nonresonant Born terms together with vector meson exchange must be considered [7,24]. A multipole analysis, using a large database for both the proton and the neutron, is needed to disentangle those contributions and extract the coupling corresponding to individual resonances. Such an approach has been attempted in Ref. [25] using the inclusive results of Ref. [9]. They obtained the value of $A_n/A_p = -0.84 \pm 0.15$ in good agreement with our experimental ratios of cross sections.

For the coherent deuteron, the extraction of the cross sections is straightforward once the missing mass peak has been identified above the background. The background shape is consistent with multiple $\pi$ final states containing at least one $\pi^0$. It has been subtracted by a smooth fit looking at each individual spectrum [22,26]. Figure 3 shows that our results lie roughly 6 times lower than those of Ref. [11].

Figure 4 displays the angular distributions at four different energies, between 650 and 780 MeV. The curve which fits our data at 678 MeV was obtained by scaling down those of Ref. [27] by a factor of 5. It is interesting to note that a satisfactory fit to our angular distributions is obtained with only the impulse approximation contribution, without much need for the rescattering terms corresponding to $\pi$ and $\eta$ meson exchange. Similar conclusions would arise from a comparison of our data with the older calculation [28] or the more recent ones [24,29] in all approaches, the impulse approximation generates good fits to our angular distributions.

The ratio of the coherent deuteron cross section to that of the free proton will scale approximately as $(2A_s/A_p)^2$. The authors of Ref. [27] had to use an $A_s/A_p$ ratio of 0.6 to fit the data of Ref. [11]. In the framework of their impulse approximation model, the fit to our new coherent

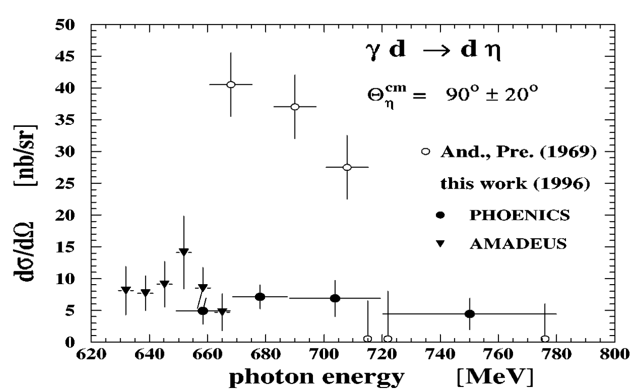


FIG. 3. Differential cross sections for the reaction $\gamma d \rightarrow \eta d$ compared to the former results of Anderson and Prepost [11].

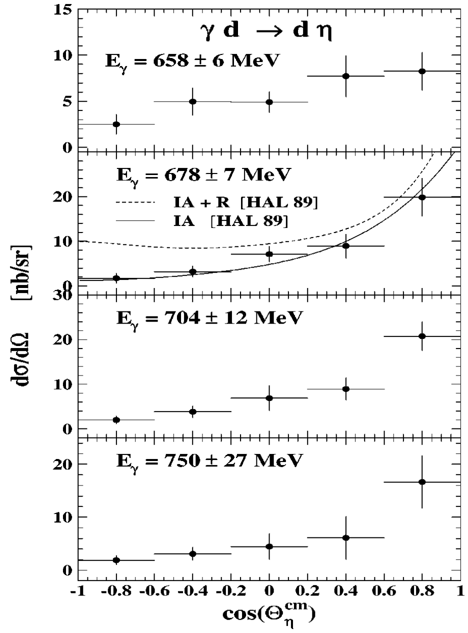


FIG. 4. Differential cross sections for the reactions $\gamma d \rightarrow \eta d$ at four energy bins between 650 and 780 MeV. For 678 MeV the results are compared to the theoretical predictions of Halderson and Rosenthal [27]. The curves were scaled down by a factor of 5 to fit the experimental points. Solid line: impulse approximation. Dotted line: impulse approximation and rescattering terms.

deuteron data brings the $A_s/A_p$ ratio down to 0.27. We can also use Eq. (1) leading to the relation [9]

$$A_s/A_p = (1/2)(1 - \sqrt{\sigma_n/\sigma_p}) \qquad (2)$$

and the average value found for the experimental ratios $\sigma_n/\sigma_p$ to determine $A_s/A_p$ in a model independent way. We find a value $A_s/A_p = 0.09 \pm 0.02$. Such a small isoscalar amplitude would bring the impulse approximation curve of Ref. [27] a factor of 9 below our data. New theoretical investigations of the coherent production mechanism are necessary to understand why the experimental cross sections are still so large compared to first order theoretical predictions.

In summary, the present work provides $\sigma_n/\sigma_p$ ratios in small energy and $\cos(\theta)$ bins measured exclusively via $\eta$-nucleon coincidences for the first time [22]. Making use of available differential cross sections for the proton [4,21], differential cross sections for the neutron may be obtained in a model independent way. Those data together with the differential cross sections for coherent $\eta$ photoproduction presented also in this Letter provide the necessary constraints to evaluate the elementary amplitudes of the $\eta$ meson photoproduction on the neutron. Further progress in this field may be expected from measurements of polarization observables on the proton [30]. Polarization data on the neutron should also come soon, from the onset of new facilities with polarized photon beams, and the development of new polarized target materials presenting a high dilution factor for polarized $D$ nuclei [31].

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