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Coherent π^0 photoproduction on the deuteron up to 4 GeV

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The differential cross section for $^2\mathrm{H}(\gamma,d)\pi^0$ has been measured at deuteron center-of-mass angles of 90° and 136°. This work reports the first data for this reaction above a photon energy of 1 GeV, and permits a test of the apparent constituent counting rule and reduced nuclear amplitude behavior as observed in elastic *ed* scattering. Measurements were performed up to a photon energy of 4.0 GeV, and are in good agreement with previous lower energy measurements. Overall, the data are inconsistent with both constituent-counting rule and reduced nuclear amplitude predictions. [S0556-2813(99)50910-2]

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Many previously measured exclusive hadronic reaction cross sections were found to obey a power-law scaling as predicted by the constituent-counting rules (CCR) [1]. These rules should apply when the energy and momentum transfer in the reaction are sufficiently large such that any macroscopic hadronic effect (such as constituent binding or motion) can be neglected and the reaction proceeds by hard scatterings only. Processes such as $\mathrm{H}(\gamma,\gamma)p$ [2], $\mathrm{H}(\gamma,p)\pi^0$ [3], and electron-proton scattering [4,5] seem to follow, at least for certain center-of-mass angles, these power-law predictions in a region where the total center-of-mass-energy is a few GeV. However, in this region, the momentum transfer per gluon exchange may not be sufficient to consider these as hard exchanges [6]. This suggests that soft wave function effects should not be neglected at these energies. The reduced nuclear amplitude (RNA) approach attempts to remove part of these effects—the soft components responsible for quark binding within the nucleons—by dividing out the empirical nucleon form factors [7,8].

Presently, a number of theoretical efforts seem to indicate that the observed power-law dependence may not be a result of quark and gluon degrees of freedom as described by the CCR [9]. Nonetheless, it is very much of interest to investigate the reason why the predictions of the CCR and RNA models seem to be accurate in some cases, and not in others. Of special interest is the question of whether nuclear reactions follow these predictions. One such reaction, $^2\text{H}(\gamma,p)n$, has been reported to follow the predicted power-law scaling at a center-of-mass angle of 90°, in a photon energy region between 1.0 and 4.0 GeV [10–12]. Perhaps even more impressive is that recent measurements of elastic electron-deuteron scattering seem to follow the predictions of both the RNA and CCR models [13].

To investigate whether this agreement extends to other nuclear reactions, we have measured one of the simplest photonuclear reactions involving a nucleus in the initial and final state, the $^2\text{H}(\gamma,d)\pi^0$ reaction. Photonuclear reactions may be the optimal choice for this investigation, because Landshoff terms (which must be considered in hadron-hadron interactions [14,15]) cannot contribute, and the effective momentum transfer [16] and differential cross sections can be large compared to similar electronuclear cross sections.

For the exclusive process A+B→C+D at high energy and large transverse momentum, dimensional analysis predicts the following constituent counting rule for the differential cross section [1]:

$$\frac{d\sigma}{dt} \propto s^{-(n-2)} f(\theta_{\text{c.m.}}), \tag{1}$$

where s and t are the Mandelstam variables, $\theta_{\text{c.m.}}$ is the center-of-mass scattering angle, $f(\theta_{\text{c.m.}})$ depends on details of the dynamics of the process, and n is the total number of elementary fields (photon, quark, etc.) in the initial and final states. For the $^2\text{H}(\gamma,p)n$ reaction, $n-2$ is 11, $n-2$ is 12 for the $^2\text{H}(e,e'd)$ reaction, and for the $^2\text{H}(\gamma,d)\pi^0$ reaction $n-2$ is 13. As mentioned above, data at a center-of-mass angle of 90° for the $^2\text{H}(\gamma,p)n$ reaction are in agreement with the CCR prediction above a photon energy of only 1 GeV [10–12]. However, data at center-of-mass angles of 52° and 36° do not agree with these predictions [12]. Furthermore, while the RNA analysis describes the electron-deuteron elastic scattering cross section above a momentum transfer squared of 2 GeV^2 [7,13], the data are also well described by conventional calculations including meson-exchange currents [17]. The RNA analysis also does not give a good description of the $^2\text{H}(\gamma,p)n$ data, even though it is expected to approach scaling at lower energies than the CCR model. Previous data for the $\text{D}(\gamma,d)\pi^0$ reaction were limited to photon energies below $E_\gamma \simeq 1$ GeV [19], and were never tested against these predictions.

Here we report on a substantial extension of existing results for the $^2\text{H}(\gamma,d)\pi^0$ reaction at deuteron center-of-mass angles (angle between the incoming and outgoing deuteron in the center of mass) of 90° and 136°. In the present experiment, an electron beam passed through a 4 or 6 % radiation length copper radiator to create an untagged photon beam, incident on a cryogenic liquid deuterium target of 12 or 15 cm length. Electron beam energies between 0.8 and 4.0 GeV, and beam currents between 10 and 30 μA were used. The High Momentum Spectrometer (HMS) in Hall C at Thomas Jefferson National Accelerator Facility, with a solid angle of 6.7 msr and a momentum acceptance of ±10% was used to detect the deuterons. The photon energy could be reconstructed from the measured momentum and scattering angle of the final state deuteron. Plastic scintillators were used to form a trigger and to provide time-of-flight information for particle identification. Drift chambers were used to measure the trajectory of the particle from which the momentum and scattering angle of the deuteron were determined. A 6.35 cm thick tungsten collimator was installed in front of the spectrometer. Although this collimator will not stop high-momentum deuterons, it was used as a cut on reconstructed quantities. Deuteron identification was obtained by reconstructing the mass from the time-of-flight measurement over a 2-m flight path between two pairs of scintillator planes in the detector hut and from the reconstructed momentum of the particle. This method identifies deuterons well at the lower photon energies, as shown in Fig. 1(a). At higher photon energies, the ratio of protons [produced largely by the $^2\text{H}(\gamma,p)n$ reaction] to deuterons entering the spectrometer was large, and a larger tail from protons strongly interacting in the first scintillator planes exists under the deuteron mass peak, as shown in Fig. 1(b). This tail was subtracted in the data analysis, and the uncertainty in the procedure adds to the systematic uncertainty for the higher photon energies.

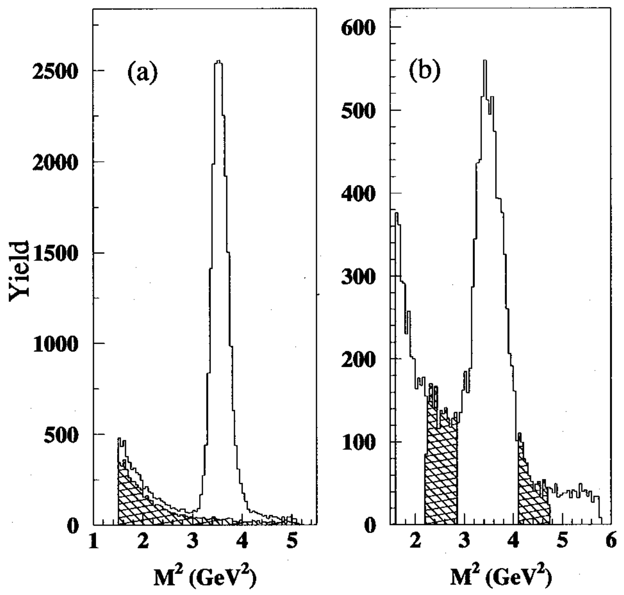

FIG. 1. Mass spectrum as determined from time-of-flight measurement and momentum reconstruction in the HMS: (a) at a photon beam energy of 1.4 GeV, (b) at a photon beam energy of 3.2 GeV. The deuteron peaks can be clearly identified. In (a) the shaded area indicates protons, probably undergoing secondary interactions, which were identified with energy loss in the scintillators. At the higher energy (b), the background under the deuteron peak is approximated by the sum of the shaded areas because energy loss cannot be used to separate protons from deuterons.

Background contributions from the target windows were removed by placing cuts on the reconstructed target position

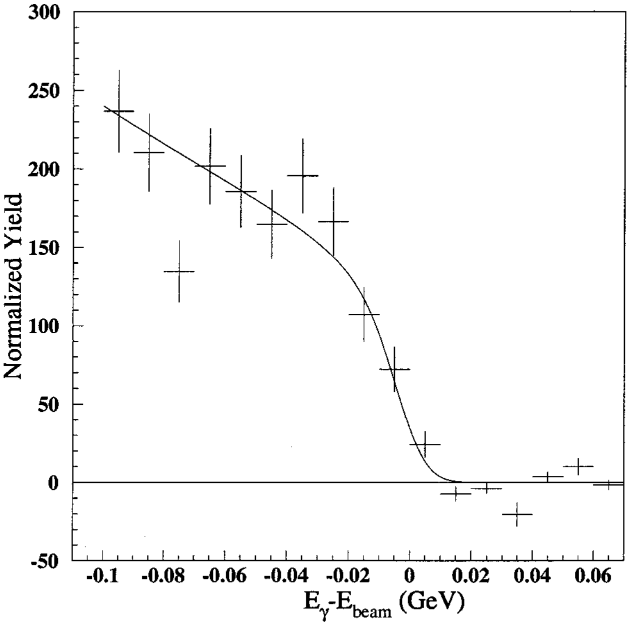

FIG. 2. Bremsstrahlung endpoint spectrum for the ^{2}H$(\gamma,d)\pi^0$ reaction at a photon energy of 1.4 GeV and a center-of-mass angle of 90°. The solid curve shows the (normalized) theoretical bremsstrahlung spectrum for single-pion production weighted with $s^{-8.6}$.

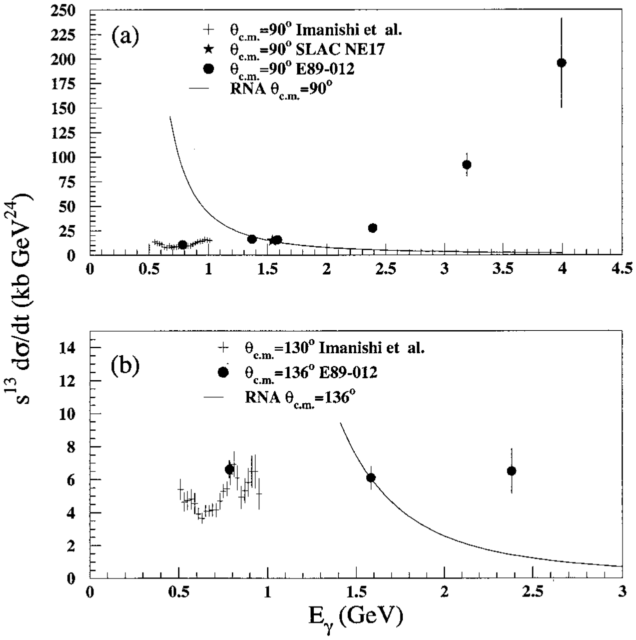

FIG. 3. The data from the present work in combination with the existing data for the ^{2}H$(\gamma,d)\pi^0$ reaction. For a center-of-mass angle of 90° (a) and for a center-of-mass angle of 136° (b). The errors bars on the present work include both systematic and statistical uncertainties. Data from Imanishi *et al.* [19] are shown as pluses, a datum extracted from the SLAC NE-17 experiment is shown as a star, and data from the present experiment are shown as solid circles. Solid curves are RNA calculations normalized to the data at 1.6 GeV.

and subtracting the yield obtained with a cell of identical dimensions that was filled with liquid hydrogen to simulate bremsstrahlung produced in the deuterium. Deuterium and hydrogen data were taken alternately during the experiment. The yield from electroproduction was measured by repeating the procedure without the radiator. This background was subtracted from the photoproduction yield with an energy dependent correction factor to take into account the modification of the electron beam flux and energy distribution by the radiator [20].

The photon energy bin limits were chosen to kinematically eliminate deuterons associated with more than single pion production processes, and to eliminate the bremsstrahlung endpoint, for which the photon flux is less well known. The former is not always *a priori* possible for this experiment, since the two pion and single pion kinematic threshold are only separated by ~25 MeV in photon energy in the worst case. However, we verified that the differential cross sections did not depend on the photon energy cut at the higher energies, and compared the measured bremsstrahlung spectra with the theoretical spectra assuming single-pion production. These theoretical bremsstrahlung spectra were calculated using a code [18] based on the the thick-target bremsstrahlung calculations of Matthews and Owens [21] in combination with the Landau spectra mimicking the energy loss tails in the radiator. The absolute uncertainty in the bremsstrahlung photon flux is estimated to be less than 3%. A typical example of an endpoint spectrum for the ^{2}H$(\gamma,d)\pi^0$ reaction, with a normalized theoretical bremsstrahlung spectrum weighted by $s^{-8.6}$ (the empirical energy dependence of the cross section) and smeared for spectrometer resolution for this process, is shown in Fig. 2. The solid curve in the figure is in good agreement with the data which show no indications of two pion production processes. A possible competing process, in our measurement indistinguishable from π^0 photoproduction, would be coherent real Compton scattering from the deuteron, but the ratio of analogous processes in hydrogen H$(\gamma,\gamma)p$ to H$(\gamma,p)\pi^0$ in a similar energy range is only a few percent [2] in the worst case.

We applied a deuteron absorption correction (15–20 %) to compensate for the inelastic deuteron reactions in the target, spectrometer windows, and detector stack. This correction was constructed from measured proton-proton and neutron-proton cross sections, parametrized as $A^{0.75}(\sigma_{pp}+\sigma_{np})$. We assign a 5% systematic uncertainty for this procedure. Furthermore, the validity of this procedure was checked by measuring ^{2}H$(e,e'd)$ in coincidence at two values of momentum transfer and comparing the calculated attenuation with the reduction of this coincidence cross section with respect to the world data set on elastic electron-deuteron scattering. The results agree much better than the 5% uncertainty. Corrections were also applied for the computer dead-time and the tracking efficiency. The overall systematic uncertainty is found to range between 6% at the lower photon energies and 20% at the highest photon energy, and is dominated by the attenuation correction and the background correction. The background subtraction is related to events observed above the photon endpoint and in a continuum in the reconstructed M^2 spectra. These events were mostly removed by subtraction of the tail under the deuteron missing mass [see Fig. 1(b)]. Some of these events however, may be due to poor reconstruction of momenta resulting from deuterons scattering inside the spectrometer. The systematic uncertainty quoted includes a contribution from the sensitivity to the choice of background subtraction procedure.

The differential cross sections $s^{13}d\sigma/dt$ as determined from our data for center-of-mass angles ($\theta_{\mathrm{c.m.}}$) of 90° and 136° are shown in Fig. 3 [18]. The data at the lowest energy are in good agreement with earlier measurements by Imanishi *et al.* [19] and extend to a photon energy of 4 GeV (2.4 GeV) for $\theta_{\mathrm{c.m.}}=90°$ (136°). An unpublished $^2\mathrm{H}(\gamma,d)\pi^0$ datum [18] extracted from the SLAC NE17 experiment [11] is also shown, and agrees well with the new data. The solid curves in the figure are RNA calculations arbitrarily normalized to the data at 1.6 GeV. It is clear that the data at both angles are inconsistent with the RNA approach. The 136° data are consistent with the CCR predicted s^{-13} scaling, while the 90° are in sharp disagreement with this prediction. Furthermore, we note that while the data at 136° do not extend to as high an incident photon energy as the 90° data do, they do cover a similar range in effective momentum transfer $(1\leqslant Q^2\leqslant 6)$ GeV^2. The recent measurements of the deuteron electric form factor $A(Q^2)$ are consistent with both the CCR and RNA predictions in a similar four-momentum transfer range $2\leqslant Q^2\leqslant 6$ GeV^2 [13]. Data for these two reactions pose a sharp contrast as both processes involve a deuteron in the initial and final states.

The invariant cross section, $d\sigma/dt$, for the 136° data was found to scale as $s^{-13.1\pm 0.2}$ and in the case of the 90° data, $d\sigma/dt\sim s^{-9.6\pm 0.4}$. This variation of the power of s with center-of-mass scattering angle is also seen in other photoreactions. The $^2\mathrm{H}(\gamma,p)n$ [12] and $\mathrm{H}(\gamma,\gamma)p$ [9] reactions were also reported to scale with varying powers of s for different center-of-mass angles. When viewed collectively, data from these photoprocesses may indicate that nuclear processes in this energy range are still dominated by soft wave function effects [6,9]. Similarly, the elastic *ed* scattering results below $Q^2=6$ GeV^2 may be more appropriately described by meson-exchange calculations than by the RNA and CCR models [17].

In summary, we have extended the sparse data set on the $^2\mathrm{H}(\gamma,d)\pi^0$ reaction up to photon energies where previous real photon experiments on hydrogen and deuterium targets started to show consistency with constituent counting rule predictions. The data at a center-of-mass angle of 136° appear consistent with constituent counting rule predictions. The data at 90° in the center-of-mass are the first above a photon energy of 1 GeV to show such a dramatic deviation from the CCR and RNA predictions.

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