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π^0 Photoproduction from Complex Nuclei*

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(Received 20 March 1972)

The photoproduction yields of π^0 mesons from D_2, Be, C, Al, Cu, Ag, and Pb targets have been measured at peak bremsstrahlung energies of 4.25, 5.6, 7.8, and 9.6 GeV. The A dependence of π^0 photoproduction is found to be almost independent of energy in this range in contrast to vector-meson dominance predictions.

The direct coupling of photons to vector mesons leads to the somewhat surprising result that photons appear to be strongly absorbed in nuclear matter despite total photon-nucleon cross sections which imply a photon mean free path in nuclei of some hundreds of fermis. This effect was first pointed out by Stodolsky[1] and has since been discussed in some detail by several authors.[2] In the language of Gottfried and Yennie,[2] this apparently strong photon absorption in nuclei arises from the interference of two amplitudes, one in which the photon interacts directly with a nucleon (one-step process) and one in which a coherent vector-meson wave photoproduced on one nucleon subsequently interacts with another nucleon (two-step process). Deep in the nucleus, these amplitudes interfere destructively at high photon energies, and the photon's ability to interact is inhibited.

Among the processes in which this one-step–two-step interference should be important are the total absorption cross section for photons on nuclei, incoherent photoproduction of π mesons, and incoherent photoproduction of ρ mesons. It is convenient to quote these cross sections on a nucleus A, in terms of the effective number of nucleons Z_{eff} or A_{eff} contributing to the cross section. For example, the total photon-nucleus cross section is written as

$$\sigma_t(\gamma A) = A_{eff}\sigma_t(\gamma N),$$

where $\sigma_t(\gamma N)$ is the total photon-nucleon cross section.

The theory has two characteristic features: (1) A_{eff} is reduced by the shadowing of the vector mesons, and (2) A_{eff} has a characteristic energy dependence and decreases with increasing energy. At low energies, the two-step process in unimportant. This energy dependence of A_{eff} is discussed particularly in the paper by Gottfried and Yennie.[2] It arises from the energy-dependent momentum difference between the photon and the vector meson, which causes the two amplitudes to get out of phase. This momentum difference, and hence the rate of phase slippage, is given by $M_V^2/2K$, where K is the photon energy and M_V is the mass of the vector meson.

Quantitative calculation of this shadowing requires an explicit model. In particular, vector-meson dominance (VMD) predicts quite definite results. These experiments can, therefore, be used as one test of VMD.

This theory has been previously experimentally tested in three processes involving complex nuclei: total photon absorption for both real and virtual photons,[3-5] incoherent ρ photoproduction,[6] and incoherent π^+ photoproduction.[7,8] None of these experiments found any energy dependence of A_{eff}. Nevertheless, all of the experiments involving real photons show some shadowing since A_{eff} is smaller than would be expected neglecting the two-step process. It should be noted, however, that the absolute value of A_{eff} predicted by the theory is sensitive to the nuclear model used.

We have undertaken to look at incoherent π^0 photoproduction with better accuracy than the previous π^+-photoproduction experiments[7,8] in the hope of casting some light on the presently ambiguous situation.

In the present experiment, a bremsstrahlung beam produced internally in the Cornell electron synchrotron impinges on a target. The two γ rays from the decay of photoproduced π^0's are detected in two lead-glass hodoscopes placed behind a sweeping magnet. Each hodoscope consists of 28 lead-glass counters each 4.4 cm×4.4 cm×38 cm (1 radiation length = 3.2 cm). The pulse heights in the hodoscope elements, which are recorded by an IBM 1800 computer, are used to determine the energy and position of the γ rays. The energy calibrations and resolutions of the detectors are found by observing electrons from elastic e-p scattering in coincidence with the recoil protons. The energy resolution is typically about 15% full width at half-maximum (FWHM). The γ-ray position resolution is 0.5 cm FWHM at 5 GeV and 2.0 cm at 1 GeV.

The system is triggered when a coincidence is observed between the two hodoscopes and the total energy in the detectors is above some threshold. This threshold energy is always set well below the minimum π^0 energy allowed by the geometry of the detectors. Figures 1(a) and 1(b) show representative γ-γ mass distributions before any cuts are placed on the data. The π^0 mass peaks are well defined. When the condition is imposed that the total energy be at least equal to the minimum-energy π^0 detectable, as dictated by the geometry, most of the low-mass background events disappear, as shown in Figs. 1(c) and 1(d). In these plots the target-out background has been subtracted.

We have measured the yield of π^0 mesons from D_2, Be, C, Al, Cu, Ag, and Pb at four peak bremsstrahlung energies, $K_0 = 4.25$, 5.6, 7.8, and 9.6 GeV. In each case the four-momentum transfers were in the range $0.10 < |t| < 0.25$ $(\mathrm{GeV}/c)^2$. Our resolution is not good enough to isolate the elastically produced π^0's. However, by using the data near the upper end of the spectrum only, we exclude π^0's arising from the decay of other particles (ω^0, n^0, etc.). Thus the π^0's of interest are produced directly, either elastically or with nucleon isobars. This distinction is important since the VMD theory, with which we wish to compare our data, predicts the same A dependence

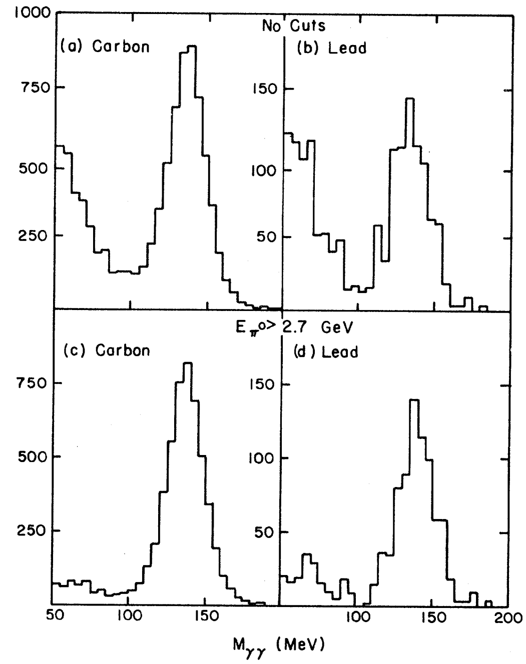

FIG. 1. Mass distribution observed from two different elements at $K_0 = 4.25$ GeV. In (a) and (b) no cuts have been put on the data, and in (c) and (d) the total energy has been required to be greater than 2.7 GeV, just slightly higher than the minimum allowed by geometry. Target-out background has been subtracted.

for π^0's produced elastically as for π^0's produced together with nucleon isobars. However, the calculations are not applicable to π^0's arising from the decay of heavier mesons.

At each machine energy A_{eff} is determined from the yield of π^0's greater than some minimum energy. The data we will present correspond to minimum energies of 2.9, 4.0, 5.8, and 7.8 GeV at our four machine energies. The fraction of inelastic events contained in the data depends on these cutoff energies. The energies above correspond to contributions from inelastic processes of approximately 30%. We have analyzed the data in various energy bins with widely varying contributions from inelastically produced π^0's and find that the results are independent of the π^0 energy interval chosen. Hence the results are insensitive to the fraction of inelastic π^0's included in the analysis.

The fraction of inelastically produced π^0's is determined by comparing the total yield of π^0's from hydrogen with the elastic yield. Elastically produced π^0's are identified by observing the recoil proton in coincidence with the π^0's. We have also observed that the shapes of the π^0 spectra for a given machine energy are very nearly the same

TABLE I. A_{eff} versus energy. Data have been normalized to $A_{eff}(D_2)$ as described in text.

Target	A_{eff} 3.2 GeV	4.6 GeV	6.4 GeV	8.6 GeV
D_2	1.54 ± 0.09	1.56 ± 0.09	1.57 ± 0.09	1.59 ± 0.09
Be	5.60 ± 0.29	4.92 ± 0.25	4.97 ± 0.25	4.47 ± 0.23
C	6.34 ± 0.32	5.83 ± 0.30	5.73 ± 0.29	5.10 ± 0.26
Al	11.4 ± 0.6	11.0 ± 0.6	10.8 ± 0.6	...
Cu	21.3 ± 1.1	19.0 ± 1.0	22.4 ± 1.4	19.9 ± 1.2
Ag	27.0 ± 1.6	31.5 ± 1.7	30.3 ± 1.8	27.7 ± 1.7
Pb	42.7 ± 2.5	41.6 ± 2.4	44.7 ± 2.6	39.6 ± 2.5

for all targets, indicating that the spectra contain approximately the same mixture of elastic and inelastic pions. Monte Carlo calculations also indicate that this should be so, since the Fermi motion has little effect on this mixture.

At each machine energy the experimental values of A_{eff} are normalized to make A_{eff} for deuterium agree with the value calculated using the formalism described below. The results of this analysis are presented in Table I and Fig. 2(a). The errors given include an uncertainty of about 5% in the ratios due to drifts in the energy calibration of the photon hodoscope and in the beam monitoring.

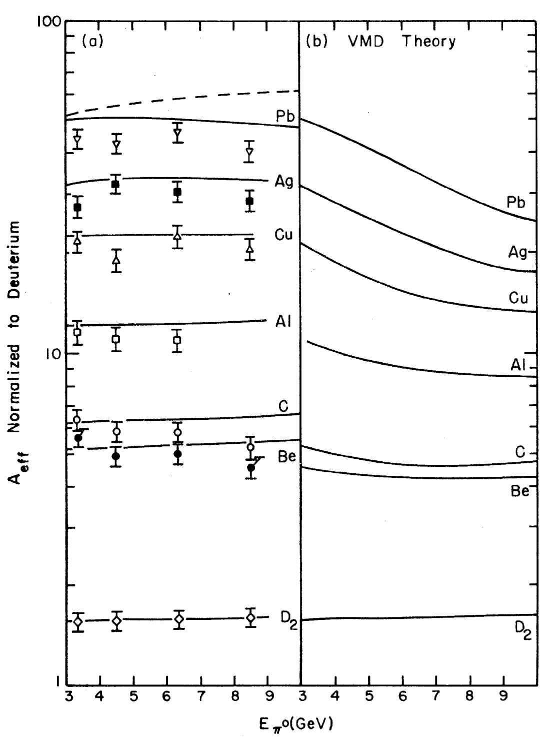

FIG. 2. (a) A_{eff} versus E_{π^0}. The data are normalized to deuterium. The solid curves assume the two-step amplitude is one quarter that demanded by VMD. The dashed curve for lead assumes zero two-step amplitude. (b) A_{eff} versus E_{π^0} as predicted by VMD.

The value of A_{eff} for deuterium is assumed to be given by

$$A_{eff}(D_2) = (1+R)[1-G(K)],$$

where

$$R = \frac{(d\sigma/dt)(\gamma n \to \pi^0 n)}{(d\sigma/dt)(\gamma p \to \pi^0 p)}$$

and the Glauber correction, $G(K)$, is approximated by

$$G(K) = 2\sigma_{\pi^0 N}(K)\langle r^{-2}\rangle/4\pi,$$

where $\langle r^{-2}\rangle$, the mean inverse square separation between the nucleons in the deuteron, is taken to be 0.3 F^{-2}.[9] We have assumed R to be 0.8, independent of energy, which is roughly consistent with our own measurements made on deuterium in which we detected the recoiling neutron or proton in coincidence with the π^0. The form assumed for $\sigma_{\pi^0 N}$, the total π^0-nucleon scattering cross section, is given below. $G(K)$ is a factor of 2 larger than might be expected otherwise, because of the assumed presence of the two-step process. According to VMD this leads to an additional correction equal to the usual correction for the absorption of the π^0 by the spectator nucleon. The Glauber corrections vary between 12 and 14%.

Figure 2(b) shows the VMD predictions given by the theory formulated by Gottfried and Yennie.[2] For all elements above carbon, the nuclear density $N(r)$ is assumed to be given by the Woods-Saxon distribution:

$$N(r) = N(0)\{\exp[(r-c)/z_1]-1\}^{-1},$$

where $C = 1.12A^{1/3}$ and $z_1 = 0.545$ F. For carbon and beryllium a shell-model distribution is used:

$$N(r) = \frac{4}{(a_0\sqrt{\pi})^3}\left(1+\frac{\delta r^2}{a_0^2}\right)\exp\left(\frac{-r^2}{a_0^2}\right),$$

where $a_0 = 1.65$ F for carbon and 1.71 F for beryllium, and $\delta = \frac{1}{6}(A-4)$. The total π^0-nucleon and ρ^0-nucleon scattering cross sections are assumed to be

$$\sigma_{\pi^0 N} = \sigma_{\rho N} = 22(1 + 1.15/K) \text{ mb}(K \text{ in GeV}).$$

The ratios of the real-to-imaginary parts of all scattering amplitudes are taken to be equal to that calculated for Compton scattering by Damashek and Gilman.[10] The value of R assumed is the same as that used in calculating A_{eff} for deuterium. It should be noted that since the present data are given relative to deuterium, the results are insensitive to the value of R. For example, a change in R from 0.8 to 1.0 increases A_{eff} for lead by only 2% relative to deuterium. Also to be noted is that a change in the Glauber correction used in the calculation of $A_{\text{eff}}(D_2)$ will result in a renormalization of the data but will not affect the theoretical calculations of A_{eff} for $A > 2$. Thus, if the Glauber correction were only half as large as we calculated (i.e., -7% instead of -14%), the experimental values of A_{eff} would all increase by 7%.

The predicted decrease of A_{eff} with increasing energy in the heavy nuclei, as shown in Fig. 2(b), is a qualitative feature of the VMD theory which is insensitive to the details of the nuclear model or to the parameters used in the calculation. The data shown in Fig. 2(a) are in striking disagreement with this qualitative feature of the theory. The essentially flat energy dependence of the data can be matched by assuming a considerably smaller two-step amplitude than is demanded by VMD. The solid curves of Fig. 2(a) are calculated assuming the two-step amplitude is one quarter that predicted by VMD. We attach little significance to the slight differences between the measured and calculated magnitudes of A_{eff} since we feel these differences are within the uncertainties inherent in the calculation. The dashed curve of Fig. 2(a) shows the prediction for lead assuming zero two-step amplitude. The increase with energy in this case is due to the decrease in $\sigma_{\pi^0 N}$ and $\sigma_{\rho N}$.

All of the experiments that have looked for this remarkable "strong absorption" of photons in nuclear matter agree that the effect is smaller than predicted by VMD. It is difficult to make a quantitative statement about the discrepancy. Indeed, if VMD is not exact, there is no reason to expect the different experiments to show precisely the same discrepancy. In most cases, the effect seems to be smaller than predicted by VMD by at least a factor of 2.

We wish to thank Professor D. Yennie and Mr. R. Spital for supplying the computer programs used to calculate the theoretical results. We are also indebted to Professor D. Yennie and Professor K. Gottfried for many illuminating conversations.

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*Work supported by the National Science Foundation.

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