can be deduced from the difference between the data and curve d, Fig. 4. Assuming that all dipions have a $\sin^2\theta_{\pi\pi}$ distribution we deduce at $M_{\pi\pi}=1.4\text{-}1.6$ BeV/c^2 the upper limit

$$d\sigma_v/dM_{\pi\pi} \leq 10^{-2}(d\sigma/dM_{\pi\pi})_{M_{\pi\pi}=M_\rho}.$$

If we attribute this possible excess to the production of a vector meson which couples directly to the photon and further assume $\Gamma_v=\Gamma_\rho$ and unit branching ratio to two pions, then we conclude that $g_{v\gamma}^2/g_{\rho\gamma}^2 \leq 10^{-2}$, $g_{v\gamma}^2$ being the direct meson-photon coupling strength. We can also deduce an upper limit for $f(1260)$ production of $2\times10^{-2}\sigma_\rho$, the factor of 2 arising from the difference in the acceptance of a 1^- and 2^+ di-pion system. Coherent photoproduction of a 2^+ state violates C conservation and the ratio of forbidden to allowed cross section of 2×10^{-2} enables one to delimit the violation.

---

*Work supported by the U. S. Atomic Energy Commission.

†Now at Physics Department, Massachusetts Institute of Technology, Cambridge, Mass. 02138, and DESY, Hamburg, Germany.

[1] N. Hicks *et al.*, Phys. Lett. 29B, 602 (1969).
[2] G. McClellan *et al.*, Phys. Rev. Lett. 23, 718 (1969).
[3] F. Bulos *et al.*, Phys. Rev. Lett. 22, 490 (1969).
[4] P. Söding, Phys. Lett. 19, 702 (1966).
[5] H. H. Bingham *et al.*, Phys. Rev. Lett. 24, 955 (1970).

Photoproduction of ω Mesons from Hydrogen and Deuterium*

H.-J. Behrend,† C. K. Lee, F. Lobkowicz, E. H. Thorndike, and A. A. Wehmann‡
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

and

M. E. Nordberg, Jr.
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

(Received 25 November 1970)

ω-meson photoproduction cross sections, summed over elastic ($\gamma N\rightarrow\omega N$) and inelastic ($\gamma N\rightarrow\omega N^*$) channels, have been measured from hydrogen and deuterium targets. The results agree with a calculation which includes only elastic and $N^*(1236)$ channels, suggesting that photoproduction of higher resonances is small. No evidence is found for $I=1$ natural-parity (e.g., A_2) exchange.

Experimental studies of ω-meson photoproduction have been limited to date to two counter experiments using complex nuclei as targets,[1,2] and a few hydrogen bubble chamber experiments.[3-7] This Letter presents results of the first counter experiment utilizing hydrogen and deuterium targets. Unlike most of the bubble chamber experiments, inelastic ω photoproduction ($\gamma N\rightarrow\omega N^*$) is detected, as well as elastic ($\gamma N\rightarrow\omega N$), providing information about the inelastic cross section. Use of both hydrogen and deuterium gives information about the spin-isospin structure of the production amplitudes. In particular, the prediction of substantial A_2 exchange, suggested by the γp, γn total hadronic cross-section difference,[8,9] is investigated.

Using a 9.1-GeV bremsstrahlung beam from the Cornell electron synchrotron, photoproduced ω mesons were detected through their $\pi^+\pi^-\pi^0$ decay. The equipment is nearly identical to that described in Ref. 1. The target was a 5-cm-diam liquid-filled cup. The charged pions from ω decay were momentum analyzed by deflection in a dipole magnet, and their tracks recorded with a wire spark-chamber system. The momentum and mass of the π^0 were determined by measurement of the energy and position of the decay γ rays. Knowing the direction, but not the energy, of the primary γ beam, all kinematical variables of the photoproduced ω could be computed. However, the degree of excitation of the target could not be determined. Thus, a sum of reactions of the type

$$\gamma+\begin{Bmatrix} p \\ d \end{Bmatrix}\rightarrow\omega+\begin{Bmatrix} N \\ 2N \end{Bmatrix}+k\pi,\quad k=0,1,2, \tag{1}$$

was measured, subject to the conditions that the ω had an energy greater than 5 GeV, and that no particles other than those from ω decay were registered by the detection equipment. Neutral particles, and charged particles below 1 GeV/c, had very small chance of registering. Thus, in

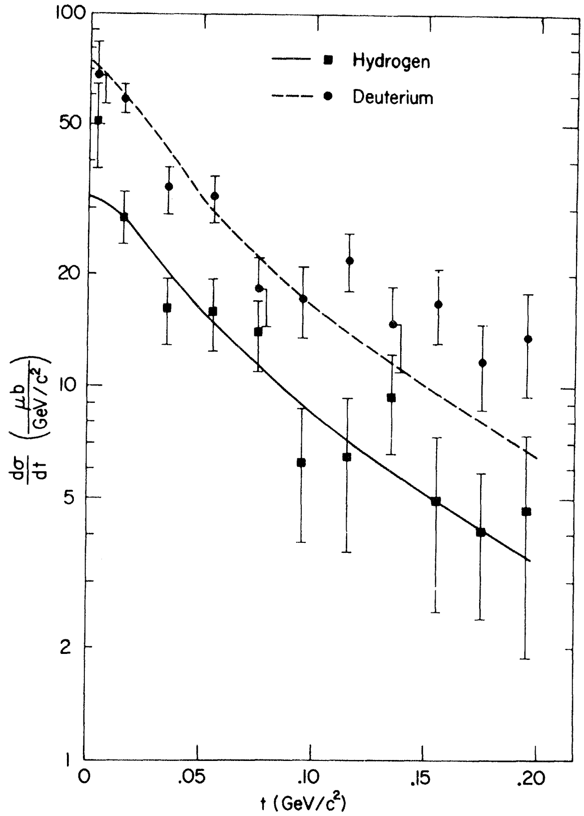

FIG. 1. ω photoproduction cross sections from hydrogen and deuterium. An overall normalization uncertainty of ±10% is not included in the plotted errors. The curve is the best fit to the data ($\alpha = 1.00$, $\delta = -0.14$) as described in the text.

addition to elastic photoproduction, ωN^* photoproduction was detected with good efficiency.[10] (Here, N^* is any of the low-lying excited states of the nucleon.)

The data-taking and analysis procedures were identical to those described in Ref. 1. A clean ω signal was obtained from both H and D. Throughout, kinematical quantities (e.g., E_γ, t) were calculated as if all events were elastic. The energy-averaged cross sections are shown in Fig. 1. The mean energy is 7.2 GeV.

The measured cross sections are written as a sum of elastic and inelastic:

$$\frac{d\sigma}{dt}(\mathrm{H}_2) = \frac{d\sigma}{dt}(\omega p) + \frac{d\sigma}{dt^*}(\omega N^*), \tag{2a}$$

$$\frac{d\sigma}{dt}(\mathrm{D}_2) = \frac{d\sigma}{dt}(\omega NN) + \frac{d\sigma}{dt^*}(\omega N^* N). \tag{2b}$$

Here t^* is the momentum transfer squared that is calculated in the inelastic case under the assumption that the event was elastic.

For elastic production on hydrogen

$$\frac{d\sigma}{dt}(\omega p) = |f_0 + f_1|^2 + |\vec{g}_0 + \vec{g}_1|^2, \tag{3}$$

where $f_I + \vec{g}_I \cdot \vec{\sigma}_N$ is the elastic photoproduction amplitude with exchange of isospin I. For elastic production from deuterium, an impulse approximation calculation, using closure, and supplemented with Glauber corrections, leads to

$$\frac{d\sigma}{dt}(\gamma d \to \omega NN) = 2\{|f_0|^2[1 + F_d(4t)] + |\vec{g}_0|^2[1 + \tfrac{1}{3}F_d(4t)] + |f_1|^2[1 - F_d(4t)]$$
$$+ |\vec{g}_1|^2[1 - \tfrac{1}{3}F_d(4t)] + |f_0|^2 G_0(t) + |\vec{g}_1|^2 G_1(t)\}. \tag{4}$$

F_d is the deuteron form factor. $G_0(t)$, $G_1(t)$ are Glauber corrections. To a good approximation,[11] $G_0 = G_1 = -0.12$.

For inelastic production from deuterium, an impulse approximation is also used[12]:

$$\frac{d\sigma}{dt^*}(\omega N^* N) = 2\frac{d\sigma}{dt^*}(\omega N^*)[1 + G_*(t^*)]. \tag{5}$$

$G_*(t^*)$, a Glauber-type correction, should differ from that for elastic production due to the rescattering of the pion from N^* decay. In the absence of a proper calculation of G_*, we set it equal to G_0, and place a large error on it: $G_* = -0.12 \pm 0.10$.

To use Eqs. (2)-(5), information about f_I, $\vec{g}_I$, and $d\sigma(\omega N^*)/dt^*$ is needed. Since the $\omega\pi\gamma$ coupling is large, one-pion exchange (OPE) processes are expected to be as important as diffractive photoproduction. Further, measurements of a significant γp, γn total cross-section difference[8,9] suggest that A_2 exchange may be important in ω photoproduction. We thus allow for diffractive production, π exchange, and A_2 exchange in interpreting our results. Under these assumptions $\vec{g}_0 = 0$.

Diffractive production gives rise to the f_0 term, which can be written $|f_0|^2 = Ae^{bt}$. In a previous experiment on ω photoproduction on complex nuclei,[1] we obtain $A = 9.6 \pm 1.2$ μb/(GeV/c)^2. b can be obtained from ρ^0 photoproduction on hydrogen,[13] $b = 8.0 \pm 1.0$.

π exchange contributes only to $\vec{g}_1$. For $|\vec{g}_1|^2$ we used an OPE calculation performed by Wolf[14] using the Bennecke-Dürr model; this calculation gives good agreement with unnatural-parity-exchange cross sections at 2.8 and 4.7 GeV, as measured in the Stanford Linear Accelerator Center (SLAC) bubble chamber.[6]

A_2 exchange contributes both to f_1 and $\tilde{g}_1$. The f_1 term will interfere with the diffractive production term, causing a difference in the ω production cross sections on protons and neutrons. Vector dominance relates this difference to the γp, γn total hadronic cross-section difference. The relevant diagrams are shown in Fig. 2, and lead at $t=0$ to

$$|f_0 \pm f_1|^2 \approx |f_0|^2 \left[1 \pm \frac{\gamma_\omega^2}{\gamma_\rho^2}\epsilon\right], \quad \epsilon = \frac{\sigma_{\gamma p}-\sigma_{\gamma n}}{\sigma_{\gamma p}+\sigma_{\gamma n}}. \tag{6}$$

This equation neglects $|f_1|^2/|f_0|^2$, and assumes that f_0 is largely imaginary. To the extent that A_2 exchange gives rise to the same t dependence as diffractive production, Eq. (6) will still be valid away from $t=0$. In interpreting our results, we write $|f_0+f_1|^2=|f_0|^2(1+\delta)$, where δ is a free parameter, to be determined. The A_2- and π-exchange contributions to $\tilde{g}_1$ do not interfere with each other, since A_2 is natural parity, and π unnatural parity. Anticipating that A_2 exchange is a small contribution, we neglect $|\tilde{g}_1(A_2)|^2$, and let the parameter δ represent the entire effect of A_2 exchange.

Finally, we assume

$$\frac{d\sigma}{dt^*}(\omega N^*) = \alpha \frac{d\sigma^{\text{OPE}}}{dt^*}(\omega N^*(1236)),$$

where α is a free parameter, to be determined, and the one-pion-exchange cross section is given by a calculation.[14] We do this because we expect $N^*(1236)$ to be the most important resonance, and the others to have similar t dependences. To the extent that the OPE calculation for $\gamma N \to \omega N^*(1236)$ is accurate, we will have $\alpha > 1$, because of contributions from the higher resonances.

We thus have two free parameters, α and δ. The best fit gives $\alpha = 1.00 \pm 0.28$, $\delta = -0.14 \pm 0.27$, and $\chi^2 = 24$ for 20 degrees of freedom. This fit is shown in Fig. 1. The error in α comes equally from the statistical error in the cross sections, uncertainty in $|f_0|^2$, error in overall normalization, and uncertainty in the N^* Glauber corrections. The error in δ is dominantly due to the statistical error in the cross sections.

The fitted value for α suggests that photoproduction of resonances higher than $N^*(1236)$ is small.[15] The fitted value for δ is quite consistent with zero. On the other hand, fits to the DESY[8] and Santa Barbara[9] total cross-section differences, when interpreted[16] with Eq. (6), suggest $\delta = +0.55 \pm 0.19$ (DESY) and $\delta = +0.45 \pm 0.11$ (Santa Barbara). Thus the value obtained in this experiment differs by two standard deviations from the values obtained from total cross-section differences.

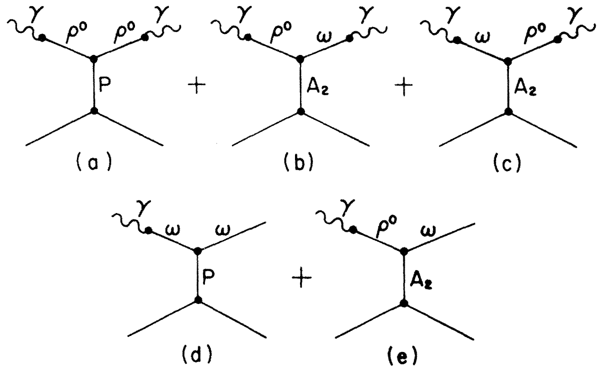

FIG. 2. Natural-parity-exchange diagrams contributing to (a)-(c) Compton scattering and (d), (e) ω photoproduction.

The authors gratefully acknowledge the support and continuing interest of Professor B. D. McDaniel and thank him for his hospitality to the Rochester group during their stay at Cornell. Dr. M. Tigner and the synchrotron operating crew are due grateful recognition for the flawless performance of the accelerator. We thank Dr. G. Wolf for performing the OPE calculations used in this experiment. Mr. J. Abramson, Mr. J. Harvey, Mr. E. May, and Mr. M. Singer helped during the running and analysis of the experiment.

---

*Research supported by the National Science Foundation.

†Present address: Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany.

‡Present address: National Accelerator Laboratory, Batavia, Ill. 60501.

[1] H.-J. Behrend, F. Lobkowicz, E. H. Thorndike, A. A. Wehmann, and M. E. Nordberg, Jr., Phys. Rev. Lett. 24, 1246 (1970).

[2] P. L. Braccini, C. Bradaschia, R. Castaldi, L. Foa, K. Lübelsmeyer, and D. Schmitz, Nucl. Phys. B24, 173 (1970).

[3] Cambridge Bubble Chamber Group, Phys. Rev. 155, 1468 (1967).

[4] Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Phys. Rev. 175, 1669 (1968).

[5] J. Ballam *et al.*, Phys. Lett. 30B, 421 (1969); Y. Eisenberg *et al.*, Phys. Rev. Lett. 22, 669 (1969).

[6] J. Ballam *et al.*, Phys. Rev. Lett. 24, 1364 (1970).

[7] Y. Eisenberg, B. Haber, E. E. Ronat, A. Shapira, and G. Yekutieli, Phys. Rev. Lett. 25, 764 (1970).

[8] H. Meyer, B. Naroska, J. Weber, M. Wong, V. Heynen, E. Mandelkow, and D. Notz, in *Proceedings of the Fourth International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September 1969,* edited by D. W. Braben and R. E. Rand (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1969), Abstract 22.

[9] W. P. Hesse, D. O. Caldwell, V. B. Elings, R. J. Morrison, F. V. Murphy, B. W. Worster, and D. E. Young, Phys. Rev. Lett. 25, 613 (1970).

[10] In the bubble chamber experiments, by contrast, the recoil proton is detected but the π^0 is not. Thus, the experiments of Refs. 3-6 detect only the final state ωp. The experiment of Ref. 7 studies the channel $\gamma n \rightarrow p\pi^-\omega$.

[11] No correction for the terms $|\vec{g}_0|^2$ and $|f_1|^2$ is shown, as the terms themselves can be neglected. $G_0(t)$ and $G_1(t)$ were evaluated assuming $\sigma_{\omega N} = 27$ mb, and that $|\vec{g}_1|^2$ and $|f_0|^2$ have the t dependence indicated in the text. The corrections are very weakly t dependent, and to a good approximation proportional to $\sigma_{\omega N}$. Uncertainty in these Glauber corrections introduces negligible error into the analysis.

[12] Equation (5) omits interference between $I=0$ and $I=1$ exchange in production of $I=\frac{1}{2}$ N^*'s; such a term will appear in the ωN^*, but not ωN^*N cross section. Neglect of this term is reasonable, since the cross section is expected to be dominated by the $I=\frac{3}{2}$ $N^*(1236)$. Effects due to the Pauli principle and NN final-state interactions, after N^* decay, have been investigated and found to be negligible.

[13] G. McClellan *et al.*, Phys. Rev. Lett. 22, 374 (1969); H. H. Bingham *et al.*, Phys. Rev. Lett. 24, 955 (1970). The published slopes are $b = 8.5 \pm 0.5$ GeV/c^{-2} at 7.6 GeV (Cornell); 7.2 ± 0.5 GeV/c^{-2} at 4.7 GeV (SLAC, p wave); 5.5 ± 0.3 GeV/c^{-2} at 4.7 GeV (SLAC, "ρ^0"). We use the p wave rather than the less conventional "ρ^0" analysis for the SLAC data. Our fitting parameters are not sensitive to the choice of b.

[14] G. Wolf, private communications. See also Ref. 6.

[15] Y. Eisenberg *et al.* (Ref. 7) find 1.85 ± 0.5 μb for the $\gamma n \rightarrow \omega p \pi^-$ cross section, compared with a calculated 0.5 μb for the $N^*(1236)$ channel, leading to $\alpha \approx 3.6$. This result is not necessarily in conflict with our result, because their experiment, performed at a lower γ energy (4.3 GeV), accepted all ω energies and momentum transfers. We, on the other hand, require momentum transfers less than 0.2 GeV/c^2, and ω energies greater than 5 GeV.

[16] We have used $\epsilon = 0.047 \pm 0.016$ (DESY) and $\epsilon = 0.038 \pm 0.009$ (Santa Barbara), obtained by evaluating fits to their cross sections at the mean energy of our experiment. For $\gamma_\omega^2/\gamma_\rho^2$, we use 11.8, obtained in our previous experiment, Ref. 1.