and $H_6(0, s)$, applying conserved vector current to relate $|H_6(0, 0)|$ to $\Gamma_{\pi^0 \to 2\gamma}$,[6] and using the experimental value[7] for $\gamma \equiv H_2(0, 0)/H_6(0, 0)$, we find that the contribution of $|M_{\mathrm{I.B.}}^{(2)}|^2$ to the total decay rate into the electron mode amounts to only $\simeq +0.06\%$ for the solution $\gamma_{\mathrm{exp}} = 0.15$ and $\simeq +0.28\%$ for the solution $\gamma_{\mathrm{exp}} = -2.07$.

In summary, our results give considerable support to the main features of the early calculations.[8] A recent re-examination of an old experiment indicates that the theoretical prediction for R given in Ref. 2 lies within 2 standard deviations of the experimental value.[9] In view of our results and the inconclusive nature of the present experimental data, we believe that a precise measurement of the ratio R is needed to test more accurately electron-muon universality in weak interactions.

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†On leave from New York University.

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Elastic Photoproduction of ω Mesons from Hydrogen, Deuterium, and Complex Nuclei*

J. Abramson, D. E. Andrews, J. Harvey, F. Lobkowicz, E. N. May, C. A. Nelson, Jr., M. Singer, and E. H. Thorndike
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 2 March 1976)

We have studied ω photoproduction using 7.5- to 10.5-GeV tagged photons. Cross sections from hydrogen lie 22% below the bubble chamber results of Ballam *et al.*, but have a similar slope. Density matrices indicate approximate s-channel helicity conservation. The proton-neutron cross-section difference is midway between zero and the value suggested by the γp-γn total-cross-section difference. Fits to the cross sections for D, Be, and Cu and those for Be, C, Al, Cu, and Pb from a previous experiment yield $\sigma_{\omega N} = 25.4 \pm 2.7$ mb and $\gamma_\omega^2/4\pi = 7.6 \pm 1.2$.

Photoproduction of ω mesons is of interest for several reasons. Among them are these: (1) The γ-ω direct coupling constant $\gamma_\omega^2/4\pi$ and the ω-nucleon total cross section $\sigma_{\omega N}$ can be determined[1-3] from the A dependence of forward photoproduction. (2) A_2 exchange contributes to ω photoproduction, giving rise to a difference in cross section from neutrons and protons. The difference in the slope of the cross sections provides information about the A_2 exchange trajectory.[4] The difference in the forward cross sections is related, through vector dominance, to the difference in total hadronic photoproduction cross sections on protons and neutrons.[5] (3) As an example of a dominantly diffractive process, the extent to which helicity is conserved is of interest.

Two counter experiments[1,2] have studied ω photoproduction from complex nuclei. A series of bubble-chamber experiments[6] have studied photoproduction from hydrogen. One counter experi-

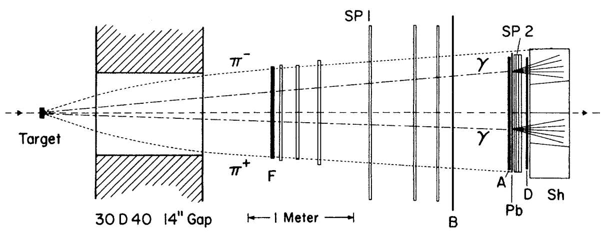

FIG. 1. Plan view of experiment.

ment[5] made measurements from hydrogen and deuterium; however, it lacked the ability to directly separate elastically and inelastically photoproduced ω's. Here we report new measurements from H, D, Be, and Cu.

The experimental arrangement is shown in Fig. 1. A tagged photon beam is incident on a target located just upstream of a 30D40 magnet. ω's are detected via the dominant decay mode, $\pi^+\pi^-\pi^0$. Charged pions are deflected by the magnet and pass through a front plane of four scintillation counters (F), six wire spark chambers (SP1), and a back plane of four counters (B). Each γ ray from π^0 decay must strike one of sixteen γ counters, each of which consists of an anticoincidence counter (A), a 1.5-radiation-length Pb converter, a defining counter (D), and an energy-measuring Cherenkov shower counter (Sh) containing an aqueous solution of lead perchlorate. Three strip spark chambers (SP2) measure shower positions. Thus the vector momenta of all ω-decay products are measured. Since the energy of the incident photon is known, the missing mass of the reaction $\gamma N \to \omega m$ can be determined. The trigger requirement was (tagged photon) $\cdot$ ($\geq$2F) $\cdot$ ($\geq$2B) $\cdot$ ($\geq 2\gamma$).

Data for H and D were collected in two separate runs, with tagged photon energies of 7.3 and 8.9 GeV for the first and 8.8 to 10.4 GeV for the second, yielding a mean energy of 8.9 GeV. Be and Cu data were taken during the first run only, at a mean energy of 8.2 GeV. Events whose topology was two charged particles and two γ rays were kinematically reconstructed. The 2γ mass resolution was ± 14 MeV; the $\pi^+\pi^-\pi^0$ mass resolution was ± 13 MeV. The 2γ mass spectrum was dominated by the π^0. For events passing a π^0 mass cut, the $\pi^+\pi^-\pi^0$ mass spectrum showed a very clean ω peak, and the ω signal was easily extracted. The missing-mass resolution was ± 140 MeV for

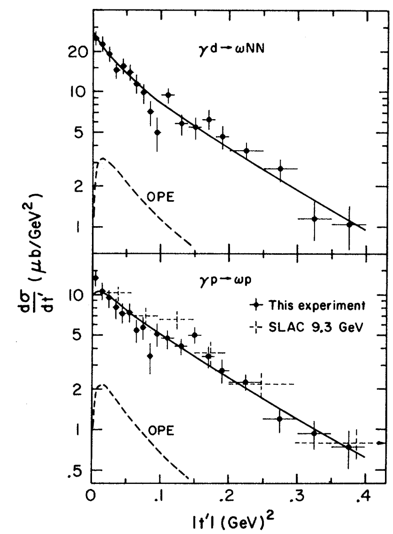

FIG. 2. Differential cross sections for $\gamma d \to \omega NN$ and $\gamma p \to \omega p$. Solid curves are fits discussed in the text. Dashed curves are the OPE contributions used in the fits. Data points labeled SLAC are from Ref. 6.

the first run and ± 160 MeV for the second run. This resolution was not good enough to separate elastic production cleanly from inelastic production, and a subtraction producedure was required. The missing-mass spectra and the procedure used to obtain a separation are given elsewhere.[7]

H and D cross sections are displayed in Fig. 2. An overall normalization uncertainty of $\pm 10\%$ is not included in the errors shown. The curve through the $\gamma p \to \omega p$ data is a fit by the form $A_p \times \exp(-b_p|t'|)$ + one-pion exchange (OPE), where $t' = t - t_{\min}$ is the square of the four-momentum transfer to the nucleon, minus its value for forward production. OPE is a zero-free-parameter calculation[8] of the one-pion-exchange contribution, which at these energies constitutes about one-sixth of the total cross section. Also shown in Fig. 2 are results from the Stanford Linear Accelerator Center (SLAC) hydrogen-bubble-chamber experiment[6] at 9.3 GeV. The two experiments agree on the shape of the cross section, but our measurements lie 22% below the points given by Ballam *et al.*[6] In fitting the cross section for the reaction $\gamma d \to \omega NN$, we use an expression[5] based on an impulse-approximation calculation, using closure and supplemented with Glauber corrections:

$$d\sigma/dt' = 2\{|f_0|^2[1+F_d(4t)-G_0(t)] + |\vec{g}_1|^2[1-\tfrac{1}{3}F_d(4t)-G_1(t)]\}. \quad (1)$$

$|f_0|^2 = A_d \exp(-b_d|t'|)$ and $|\vec{g}_1|^2$ are the spin-nonflip $I=0$ exchange and spin-flip $I=1$ exchange contributions for a single nucleon. For $|g_1|^2$ we use the OPE calculation.[8] F_d is the deuteron form factor, and G_0 and G_1 are Glauber corrections (both taken to be 0.12). The results of the fits are $A_p = 8.8 \pm 0.7$ μb/GeV^2, $b_p = 7.1 \pm 0.5$ GeV^{-2}, $A_d = 7.4 \pm 0.5$ μb/GeV^2, and $b_d = 6.9 \pm 0.5$ GeV^{-2}.

A primary goal of this experiment was a measurement of the neutron-proton cross-section difference, presumed due to $I=1$ natural-parity exchange interfering with the dominant $I=0$ natural-parity exchange term (e.g., A_2 exchange interfering with Pomeron exchange). Through vector dominance, this difference is related to the γp-γn total hadronic cross-section difference. With a few approximations,[5,9] one obtains

$$\delta \equiv A_p/A_d - 1 = 1.3(\gamma_\omega/\gamma_\rho)^2\epsilon, \qquad (2)$$
$$\epsilon \equiv (\sigma_{\gamma\rho} - \sigma_{\gamma n})/(\sigma_{\gamma\rho} + \sigma_{\gamma n}).$$

Because $(\gamma_\omega/\gamma_\rho)^2 \approx 10$, a small total-cross-section difference ϵ implies a large ω-cross-section difference δ. Fits[10] to the total hadronic cross-section measurements yield $\epsilon = 0.026 \pm 0.009$, implying $\delta = 0.34 \pm 0.12$. From the fits to the cross sections shown in Fig. 2, we obtain $\delta = 0.20 \pm 0.12$, a value consistent with the total-hadronic-cross-section difference. If we require $b_p = b_d$, we find $\delta = 0.18 \pm 0.09$, marginally consistent with no A_2 exchange.

The A_2-Pomeron interference model of Barker, Gabathuler, and Storrow[4] implies a slope difference $b_p - b_d \approx 4\delta$, 0.8 ± 0.5 for our value of δ. This is consistent with our measured slope difference of 0.15 ± 0.74. The density matrices for the reactions $\gamma p \to \omega p$ and $\gamma d \to \omega NN$ are displayed for the helicity frame in Fig. 3. It is seen that s-channel helicity conservation (SCHC) ($\rho_{00} = \mathrm{Re}\rho_{10} = \rho_{1-1} = 0$) is well satisfied at small t, confirming the SLAC bubble chamber results.[6] For the reaction $\gamma p \to \omega p$, the density matrix deviates from zero at large t; the deviations are smaller in the reaction $\gamma d \to \omega NN$, suggesting that the breakdown of SCHC in $\gamma p \to \omega p$ is due to A_2 exchange.

The complex-nucleus data (Be, Cu) have t distributions displaying characteristic forward peaks, and density-matrix elements consistent with SCHC, as expected. Forward cross sections are 0.37 ± 0.05 mb/GeV^2 for beryllium and 9.6 ± 1.2 mb/GeV^2 for copper. These numbers are to be compared with 0.41 ± 0.03 and 10.6 ± 1.0 mb/GeV^2 obtained in our earlier experiment[1] (extrapolated in energy).

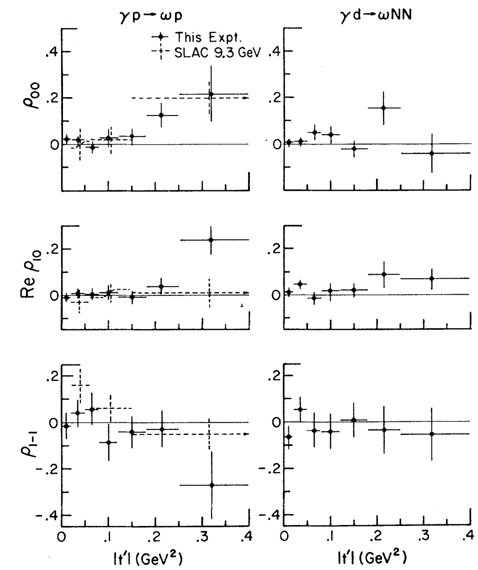

FIG. 3. Density-matrix elements for the reactions $\gamma p \to \omega p$ and $\gamma d \to \omega NN$, evaluated in the helicity frame. Data points labeled SLAC are from Ref. 6.

An important motivation for the present experiment was the disagreement between the values of the ω-photon direct coupling constant $\gamma_\omega^2/4\pi$ as obtained in our earlier experiments[1,3] ($7.6^{+1.8}_{-1.1}$) and as obtained in two colliding-beam experiments[11,12] (3.7 ± 0.7 and 4.6 ± 0.5). Results obtained in the present experiment and Ref. 7 allow us to make two (small) corrections to the earlier results.

In our previous analysis, the subtraction for inelastic contamination ($\gamma A \to \omega N^*$nucleons) to the elastic reaction ($\gamma A \to \omega$ nucleons) was based on a one-pion exchange calculation of $\gamma N \to \omega\Delta(1236)$. Using measured[7] values of $\gamma N \to \omega m$ for the subtraction lowers the elastic beryllium cross section by 10%, the lead cross section by 3.5%, and cross sections for intermediate nuclei by intermediate amounts.

Most nuclei do not contain equal numbers of protons and neutrons, and therefore a correction factor $1 + [(Z-N)/A]\delta$ is required to allow for $I=1$ natural-parity exchange interfering with diffractive production. The measurement of δ reported here allows that correction to be applied.

We subjected the complex-nucleus cross sections from our previous experiment[1] and the D, Be, and Cu cross sections from the present experiment to an optical-model analysis, using $\gamma\omega^2/4\pi$, $\sigma_{\omega N}$, and α_ω as parameters. As expected, the data did not determine α_ω with any precision. (The fitted value was $\tan^{-1}\alpha_\omega = -28° \pm 19°$.) We therefore fixed α_ω at -0.24 (a value suggested by several external considerations) and fitted with two parameters, $\sigma_{\omega N}$ and $\gamma_\omega^2/4\pi$, obtaining $\sigma_{\omega N} = 25.4 \pm 2.7$ mb, $\gamma_\omega^2/4\pi = 7.6 \pm 1.2$, $\chi^2 = 1.3$, for 6 degrees of freedom. If we set $\sigma_{\omega N} = \sigma_{\rho N}$ (27 ± 2 mb), and allow for a 7% error in the absolute normalization of the cross sections, we obtain $\gamma_\omega^2/4\pi = 8.3 \pm 1.1$, little changed from our previous result, and substantially above the values from Refs. 11 and 12.

The SLAC natural-parity hydrogen cross section[6] combined with our measurement of δ allows an independent determination of $\gamma_\omega^2/4\pi$. Under the assumptions $\sigma_{\omega N} = 27$ mb, $\alpha_\omega = -0.24$, one obtains $\gamma_\omega^2/4\pi = 7.6 \pm 1.6$.

The above analyses make the "diagonal approximation," that is, they neglect terms $\varphi N \to \omega N$ and $\omega N \to \varphi N$. Ross and Stodolsky[13] first pointed out that this may not be valid, and Bauer and Yennie[14] have recently called attention to the problem. Optical-model studies by ourselves and by Bauer and Yennie show that the effect of the off-diagonal terms is to change all cross sections but not significantly alter the A dependence. Consequently, the values of α_ω and $\sigma_{\omega N}$ obtained above are unaffected. If the eigenstates in nuclear matter are a mixture of $\omega - \varphi$ that is rotated from ω, φ by $\sim 5°$, as suggested by quark-model considerations, then all ω-photoproduction cross sections are lowered by $\sim 10\%$ and the values of $\gamma_\omega^2/4\pi$ obtained above will also be lowered by 10%. If one takes the alternative viewpoint that the difference between photoproduction and colliding-beam experiments is due entirely to the off-diagonal terms, then an angle near 20° is required.

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[8]We have scaled the OPE cross section by a factor 0.75 because (a) the 9.3-GeV SLAC experiment (Ref. 6), which reports $\gamma p \to \omega p$ cross sections about 30% above ours, measures the unnatural parity exchange contribution as 0.97 times the OPE calculation, and (b) the OPE calculation for $d\sigma(\gamma N \to \omega\Delta(1236))/dt$ is about 30% above our measurement (Ref. 7). This scaling has little effect on our results.

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