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MEASUREMENT OF THE PHOTOPRODUCTION PHASES OF THE ϱ, ω, AND Φ MESONS.

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MEASUREMENT OF THE PHOTOPRODUCTION PHASES OF THE ϱ, ω, AND Φ MESONS.

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ABSTRACT. -

We measured 30000 wide-angle electron-positron pairs from the reaction $\gamma + p \to p + e^+ + e^-$ in the invariant mass region $500 \lesssim m \lesssim 1060$ MeV. The photoproduction amplitudes of the ϱ, ω, and Φ mesons were measured to deviate from being pure imaginary by $37.5^{o}{}^{+2.8^o}_{-3.1^o}$, $29.6^{o}{}^{+15.5^o}_{-12.9^o}$, $3.4^{o}{}^{+5.3^o}_{-4.2^o}$ respectively.

We determined, for the process $\gamma p \to pV$ $(V \to e^+e^-)$, the ratio of the real to imaginary part of the forward photoproduction cross section

$$\frac{d\sigma}{dt}\bigg|_{t=0} \left[\gamma p \to pV \ \ (V \to e^+e^-)\right]$$

for the three vector mesons $V = \varrho$, ω, and Φ, by studying with the 2.7 GeV bremsstrahlung beam of DESY the e^+e^- yields of the reaction

$$\gamma + p \to p + e^+ + e^- \qquad (1)$$

in the energy region 3.0-7.2 GeV and in the e^+e^- invariant mass range $500 < m < 1060$ MeV.

Four diagrams contribute to the reaction (1) (Fig. 1a). The first two are the Bethe-Heitler diagrams which can be calculated[1]. The third one is the diffraction production diagram where the e^+e^- pairs are coming from leptonic decays of ϱ, ω, and Φ. The last diagram represents the e^+e^- contribution when the vector mesons are produced via one-pion exchange or inelastic channels.

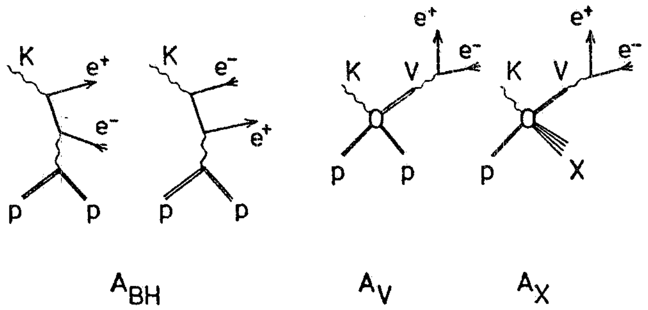

FIG. 1a - Feynman diagrams for reaction (1).

The second order, the e^+e^- pair production rate is expressed by

$$R \propto |A_{BH}|^2 + \Big|\sum_{V(V=\varrho,\,\omega,\,\Phi)} A_V\Big|^2 + |A_X|^2 + 2A_{BH}\cdot \mathrm{Re}\left\{\sum_V A_V\right\}^{(*)} + \text{QED terms connected to more than two } \gamma \text{ rays}. \tag{2}$$

In the framework of the VDM, A_V is parametrized as

$$A_V \propto \frac{m_V^2}{m^2}\,\frac{i\,e^{i\varphi_V}}{m_V^2 - m^2 - i\,m_V\Gamma_V}\sqrt{\frac{d\sigma_V}{dt}\,\frac{\Gamma_V}{m_V}}\,, \tag{3}$$

using the notation

$$\frac{d\sigma_V}{dt} = \frac{d\sigma}{dt}\left(\gamma p \to pV\,(V \to e^+e^-)\right) := \frac{d\sigma}{dt}\left(\gamma p \to Vp\right)\Big|_{t=0} \cdot e^{b_V t} \cdot BR_{e^+e^-}^{(2)}\,.$$

Here m_V is the mass of the vector meson, Γ_V its width, $\varphi_V + \pi/2$ is the relative phase between the vector meson photoproduction amplitude and the BH amplitude (which is real), b_V is the slope of the differential cross section for vector meson photoproduction on protons, and m and t are the invariant mass and the momentum transfer of the e^+e^- pair, respectively.

It follows from charge-conjugation invariance that the interference term in (2) between the Bethe-Heitler and the Compton amplitudes is antisymmetric under exchange of e^+ and e^-. Hence, the effect of the interference term consists in producing an asymmetric distribution of the experimental events as a function of any kinematical variable which is antisymmetric in the four-momenta p_+ and p_-. Such an asymmetry is a measurement of the interference term and consequently of the photoproduction phase φ_V. Any contributions to the interference term due to second order QED terms have been estimated[3] to be about 0.1 % of the BH rate and have therefore been neglected.

The apparatus (Fig. 1b) and the experimental procedure are the same as described elsewhere[4] in detail. In particular let us recall that our mass resolution is 20 MeV (FWHM) at $m = 1$ GeV.

(*) OPE (spin-flip amplitude) and inelastic amplitudes do not interfere with the Bethe-Heitler term.

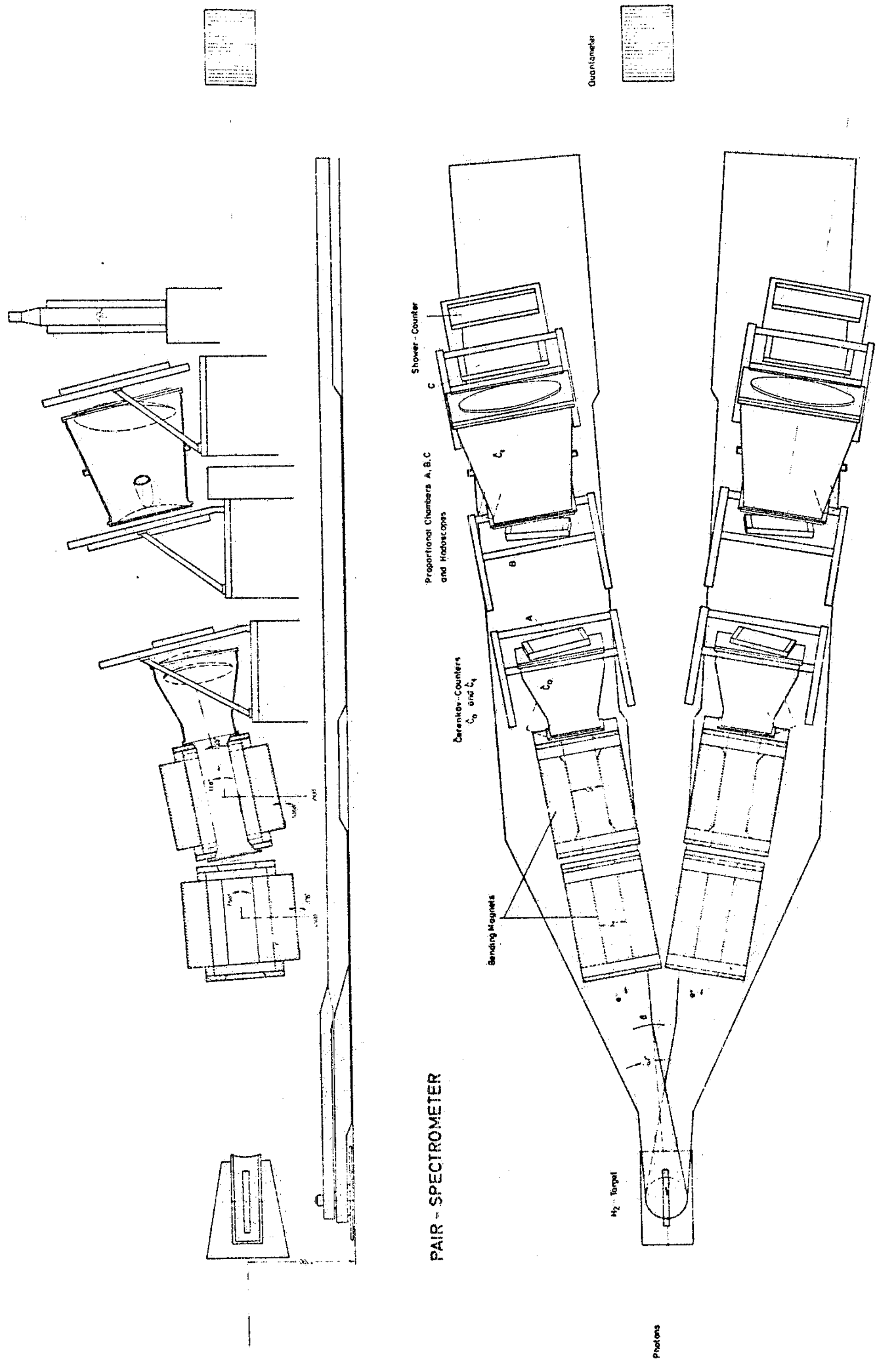

FIG. 1b - Plan and side view of the spectrometer

We have taken data with a beam top-energy K_{max} = 7.2 GeV, a central spectrometer momentum p_o = 2700 MeV at three spectrometer opening angles $\theta = 13^o$, 15^o and 16^o, and a fourth setting was defined by K_{max} = 6.0 GeV, p_o = 1700 MeV, and $\theta = 13^o$. For each setting, the same amount of data was collected for each of the two spectrometer polarity combinations in order to cancel out minor asymmetries of the apparatus.

The total number of e^+e^- events, measured in the mass range $500 \leq m \leq 1060$ MeV, is 29217 which is to be compared with Monte-Carlo predictions of 22576 ± 280 events attributed to Bethe-Heitler and 7106 ± 160 to $\varrho + \omega + \Phi$ production. The Bethe-Heitler rate is corrected for second order(5) and inelastic(1, 6) terms and is normalized to the collected number of equivalent quanta.

The invariant mass spectrum of the data collected at 13^o is shown in Fig. 2. The interference spectra for the four different setting are shown in Fig. 3.

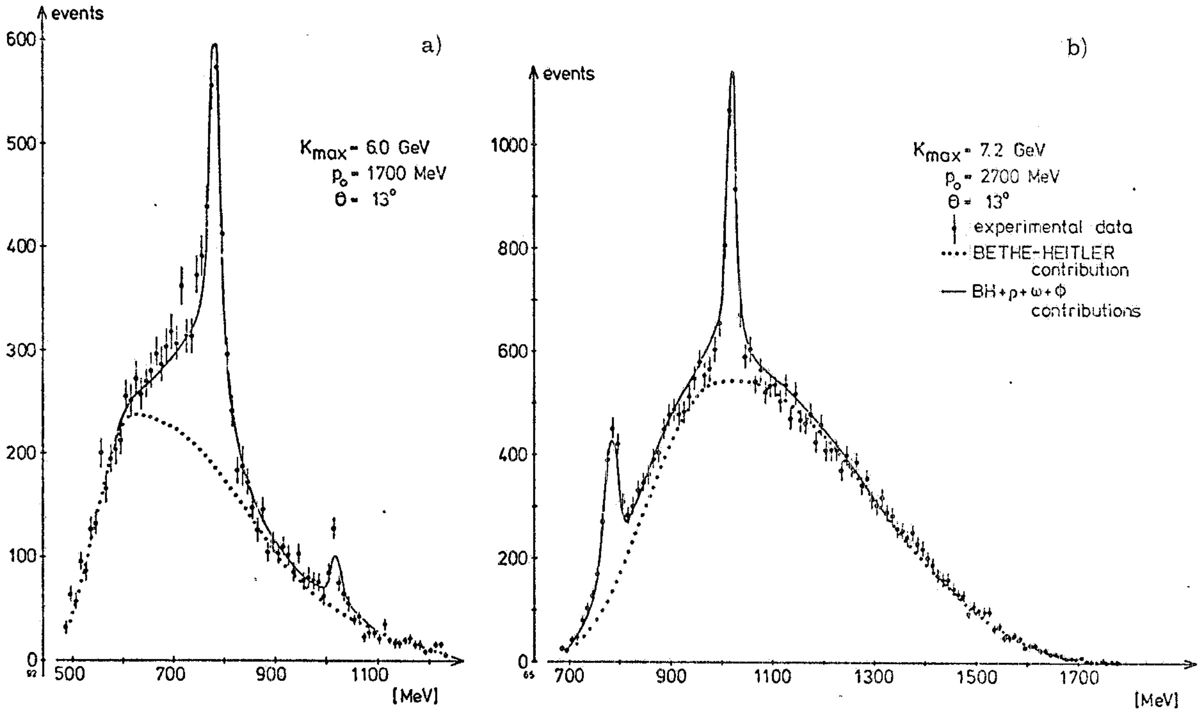

FIG. 2 - e^+e^- effective distribution. The open circles are the calculated contributions of the BH processes, normalized to the collected number of equivalent quanta. The solid line shows the calculated contribution of the BH processes together with the diffractive ϱ, ω, and Φ photoproduction, the $\varrho + \omega$ inelastic effects, and ω-OPE production.
a) K_{max} = 6.0 GeV, p_o = 1700 MeV, $\theta = 13^o$; b) K_{max} = 7.2 GeV, p_o = 2700 MeV, $\theta = 13^o$.

Due to the large uncertainties in the calculation of the ϱ, ω, and Φ inelastic and of the ω OPE contributions to the invariant mass yield, only the measured interference pattern has been used to fit the photoproduction phases.

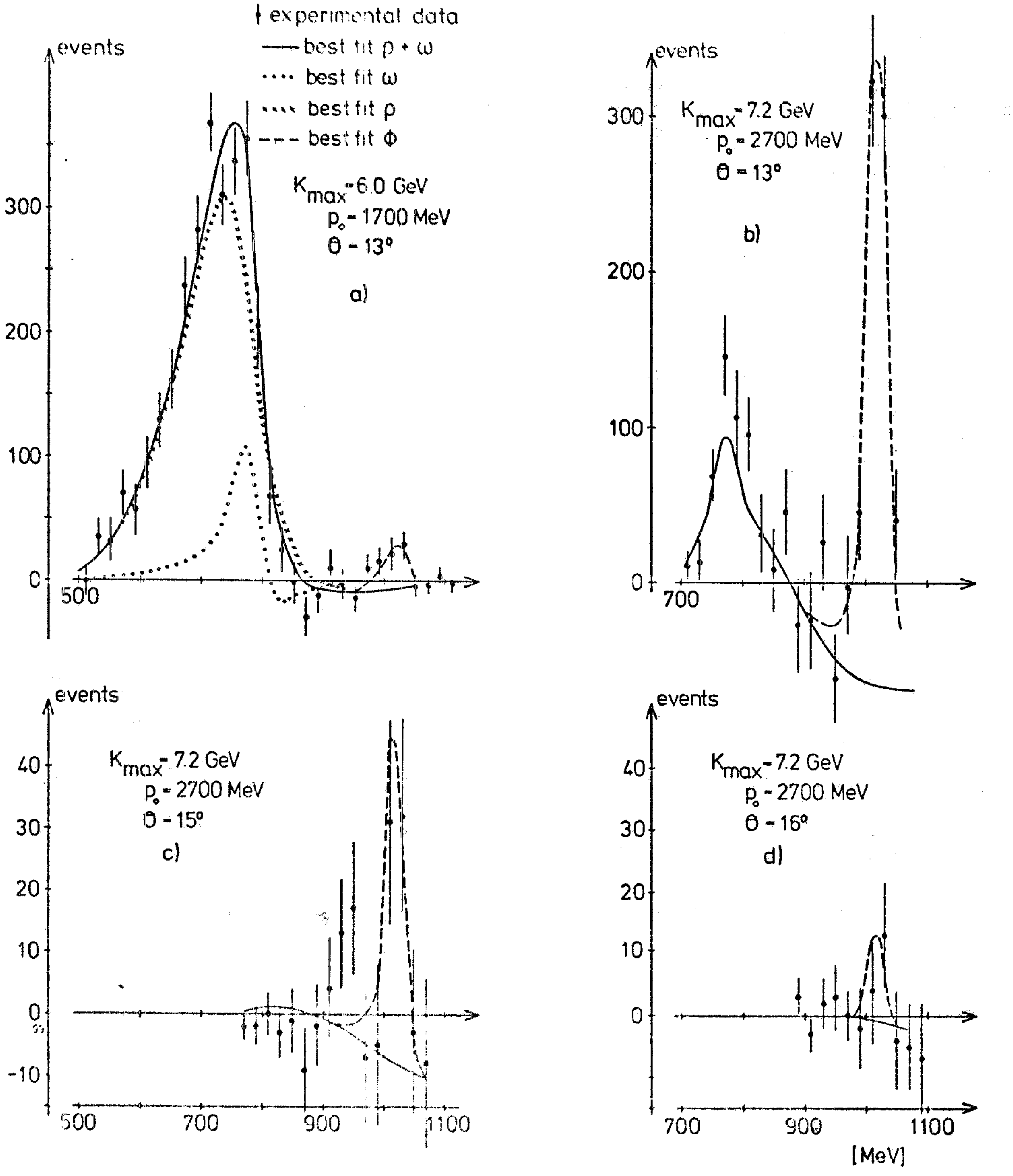

FIG. 3 - Spectrum of interference events. The solid line shows the best fit to the data with the $\varrho + \omega$ interference term of eq. (2), using m_ϱ = 767.6 MeV, Γ_ϱ = 150.9 MeV, C_ϱ = 4.55 nb GeV^{-2}, φ_ϱ = 37.5°, C_ω = 0.735 nb GeV^{-2}, φ_ω = 29.6°. In Fig. a) the open circles and the crosses show the ϱ and ω contributions also separately. The dashed line is the best fit to the data with the Φ interference term of eq. (2), using m_Φ = 1023.6 MeV, C_Φ = 0.98 nb GeV^{-2}, and φ_Φ = 3.44°.

a) K_{max} = 6.0 GeV, p_o = 1700 MeV, θ = 13° ; b) K_{max} = 7.2 GeV, p_o = 2700 MeV, θ = 13°;
c) K_{max} = 7.2 GeV, p_o = 2700 MeV, θ = 15° ; d) K_{max} = 7.2 GeV, p_o = 2700 MeV, θ = 16°.

Results for the ϱ and the ω.

We fitted the ϱ and ω interference contribution of eq. (2) to the data between 500 and 960 MeV, using m_ϱ, Γ_ϱ, φ_ϱ, $d\sigma_\varrho/dt$, m_ω, $d\sigma_\omega/dt$, and φ_ω as free parameters.

We have used $\Gamma_\omega = 10$ MeV(7), $b_\varrho = 6.3\ \mathrm{GeV}^{-2}$ (9) and $b_\omega = 6.7\ \mathrm{GeV}^{-2}$ (9). Γ_ω is assumed to be mass independent, while Γ_ϱ has been parametrized(8) as

$$\Gamma_\varrho(m) = \Gamma_\varrho \frac{m_\varrho}{m} \left(\frac{m^2 - 4m_\pi^2}{m_\varrho^2 - 4m_\pi^2}\right)^{3/2} \frac{1 + \frac{R^2}{4}(m_\varrho^2 - 4m_\pi^2)}{1 + \frac{R^2}{4}(m^2 - 4m_\pi^2)} .$$

The skewness parameter R was also left free in the fit.

The energy dependence of the photoproduction cross section has been introduced using the measured values of(9, 7) as

$$\left.\frac{d\sigma}{dt}\right|_{t=0} (\gamma p \to p\varrho \to (\varrho \to e^+e^-)) = C_\varrho\left(1 + \frac{6\ \mathrm{GeV}^2}{K^2}\right)\ \mathrm{nb\ GeV}^{-2} ,$$

$$\left.\frac{d\sigma}{dt}\right|_{t=0} (\gamma p \to p\omega \to (\omega \to e^+e^-)) = C_\omega\left(1 + \frac{1.4\ \mathrm{GeV}}{K}\right)\ \mathrm{nb\ GeV}^{-2} .$$

The published values of $C_\varrho = 3.65 \pm 0.73$ (7, 9), $C_\omega = 0.7 \pm 0.14$ (7, 9), $m_\varrho = 770 \pm 3$ MeV(7), $\Gamma_\varrho = 150 \pm 3$ MeV(7) and $m_\omega = 782.7 \pm 3$ MeV(7) have been further used as additional degrees of freedom of the fit(11).

In fitting the interference term of eq. (2), we used the program MINUIT(12). The errors quoted are true (MINOS) 1σ errors. The best fit is plotted in Fig. 3 (solid line), and the corresponding parameters are listed in Table I. The resulting contributions from the ϱ and the ω are shown separately in Fig. 3a.

TABLE I - Fitted parameters(x)

m_ϱ	767.6 ± 2.7 MeV		
Γ_ϱ	150.9 ± 3 MeV		
R	$0.05 \pm 0.52\ \mathrm{GeV}^{-1}$		
C_ϱ	$4.55 \pm 0.32\ \mathrm{nb\ GeV}^{-2}$	$\frac{\chi^2}{NDF} = \frac{58}{47}$	
m_ω	783.3 ± 2.9 MeV		
C_ω	$0.735 \pm 0.13\ \mathrm{nb\ GeV}^{-2}$		
φ_ϱ	$37.5^\circ\ {}^{+2.9^\circ}_{-3.1^\circ}$		
φ_ω	$29.6^\circ\ {}^{+15.5^\circ}_{-12.9^\circ}$		

(x) - The quoted errors are 1σ MINOS errors.

To be sure that the phase φ_ρ is not affected by the ω parameters, we repeated the fit leaving out the mass bins from 760 to 820 MeV, where the ω contribution depends strongly on the φ_ω value. The best fit results did not change.

Results for the Φ.

Fitting for φ_Φ was done in the mass region $950 < m < 1050$ MeV. The cross section

$$\left.\frac{d\sigma}{dt}\right|_{t=0} (\gamma p \to p\Phi(\Phi \to e^+e^-))$$

was parametrized(7, 10, 11) as

$$C_\Phi(1 - e^{-\frac{K}{2.73\,(\mathrm{GeV})}})\ \mathrm{nb\ GeV}^{-2}\ .$$

In order to study the effect of C_Φ and m_Φ on the phase value, these parameters were allowed in the fit to vary around the published values $C_\Phi = 0.9 \pm 0.13$ nb GeV^{-2} (7, 10) and $m_\Phi = 1020 \pm 3$ MeV(7, 10). The slope b_Φ was taken as 5.5 GeV^{-2} (10) and the width Γ_Φ was set = 4 MeV(7). The result of the fit is shown in Figs. 3 and 4 and the best fit parameters are given in Table II.

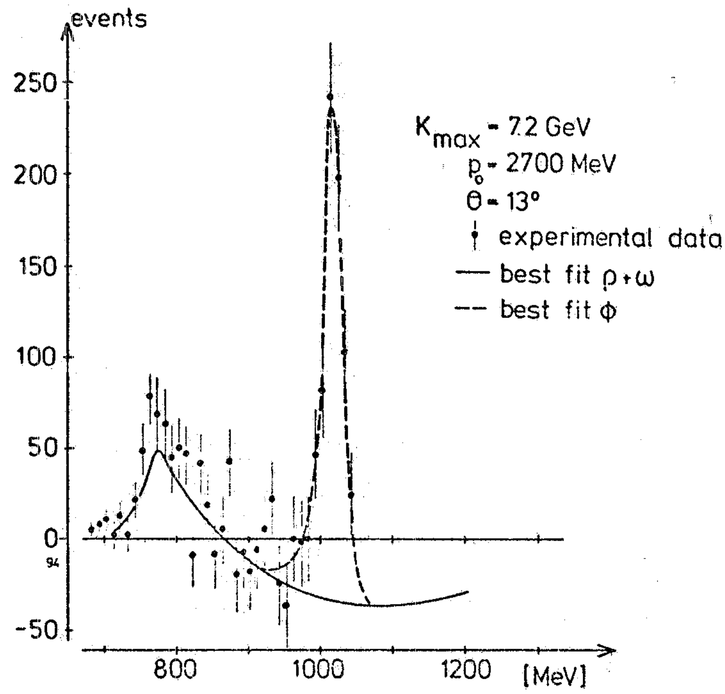

FIG. 4 - Interference spectrum as in Fig. 3b, plotted in 10 MeV bins.

TABLE II - Fitted parameters(x)

φ_Φ	$3.44^\circ \begin{smallmatrix}+5.3^\circ \\ -4.2^\circ\end{smallmatrix}$	
C_Φ	0.98 ± 0.12 nb GeV^{-2}	$\frac{\chi^2}{NDF} = \frac{7.6}{9}$
m_Φ	1023.6 ± 2 MeV	

(x) - The quoted errors are 1σ MINOS errors.

The sensitivity of φ_Φ to the ϱ tail under the Φ peak was found negligible (a change of $\pm 20\%$ of the ϱ tail values affects φ_Φ by $\pm 1.5^o$).

In Figs. 2 and 5 we show the various ϱ, ω, and Φ contributions to the e^+e^- invariant mass yield. The ϱ contributions are calculated according to our best fit parameter. The ω and Φ contributions are calculated using photoproduction cross sections into e^+e^- pairs as from refs. (9, 10) and φ_V from our fit. The inelastic ϱ and ω production was estimated from ref. (13) and the ω OPE contribution from ref. (14).

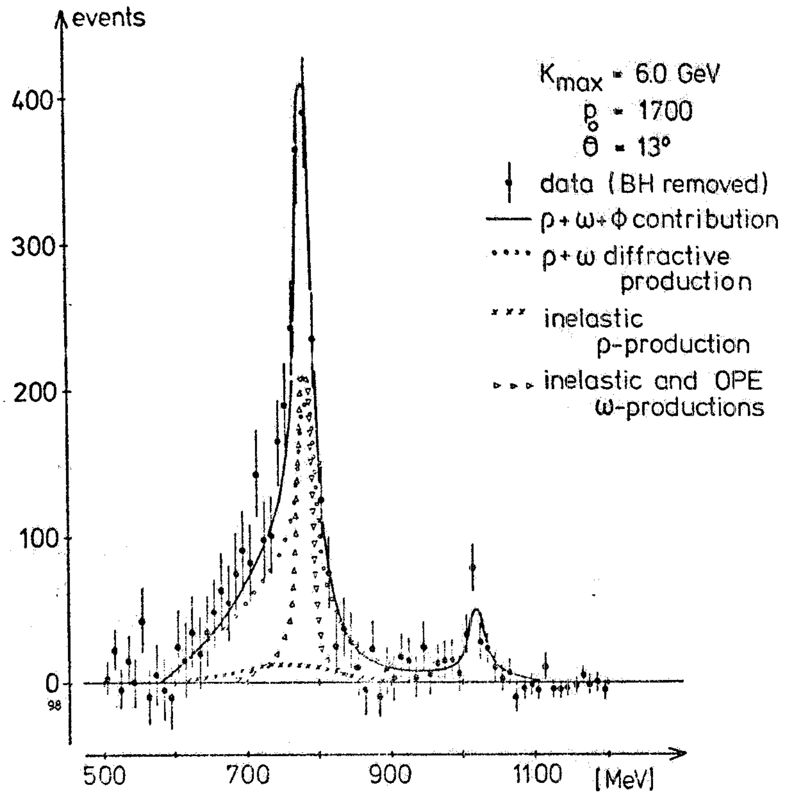

FIG. 5 - e^+e^- mass yield for K_{max} = 6.0 GeV, p_o = 1700 MeV, and = 13° after removing the calculate BH contributions (see also Fig. 2a). Shown are the separate effects of $\varrho + \omega + \Phi$ diffractive production, inelastic ϱ production, ω production via OPE, and inelastic ω production. The combined sum of these effects is indicated by the solid line.

Summary.

By studying the interference term between the Compton and the Bethe-Heitler amplitudes, we measured again the ϱ photoproduction cross section into lepton pairs, quite well in agreement with the published values[9], but our measurement does not prove more sensitive than previous experiments[7, 9, 10] with regard to the parameters C_ω, C_Φ, as well as to the ϱ, ω, and Φ mass values.

The major result of the experiment concerns the measurement of the ϱ, ω, and Φ photoproduction phases. φ_Φ is measured to be $3.4^o\,{}^{+5.3^o}_{-4.2^o}$; this is consistent with the ΦN scattering being purely imaginary. The ϱ and ω nucleon scattering are found to deviate from a pure absorptive mechanism by $37.5^o\,{}^{+2.8^o}_{-3.1^o}$ and $29.6^o\,{}^{+15.5^o}_{-12.9^o}$, respectively.

A breakdown of the simple "ϱ-photon analogy" and an anomalous large real part in the ϱ photoproduction amplitude is expected as a dynamical consequence of meson instability inside the nucleous. This effect has been qualitatively estimated to be of the order of $\frac{2\Gamma_V}{m_V} \frac{\sigma_T(\pi N)}{\sigma_T(VN)}$ (13). Numerically, this amounts to $\sim 22^o$ for the ϱ, independent of energy, while it is negligible for the ω. On the other hand, because of the $\varrho - \omega$ mass mixing effect, φ_ω has to be reduced by $\sim 11^o$ according to ref. (16).

Taking into account such corrections, our result is consistent, inside the errors, with a small refractive part of the Compton amplitude also for the ϱ and ω nucleon forward scattering, as is expected if the reaction proceeds via Pomeron exchange.

Our measured phase values may be compared with the values $\varphi_\omega - \varphi_\varrho = 41^o \pm 22^o$, $\varphi_\varrho = 11.8^o \pm 4.4^o$, and $\varphi_\Phi = 25^o \pm 15^o$ obtained by the DESY-MIT group at K = 5.6 GeV(17, 18). The ϱ and ω phase values have also been measured at DNPL(19) to be $\varphi_\omega - \varphi_\varrho = 118^{o\,+13^o}_{\;\;-22^o}$ and $\varphi_\varrho = 16.5^o \pm 6.2^o$ at K = 3.6 GeV.

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$$\left.\frac{d\sigma}{dt}\right|_{t=0} (\gamma p \to \omega p) = D\left(1 + \frac{1.4\ (\mathrm{GeV})}{K}\right) \quad \text{with} \quad D = 9.3 \pm 1.7\ \mu b\ \mathrm{GeV}^{-2} .$$

The energy dependence of the ϱ photoproduction cross section has been read off from the data in ref. (9). The cross section values are taken, according to the Yennie approach, from ref. (9) as

$$\left.\frac{d\sigma}{dt}\right|_{t=0} (\gamma p \to p\varrho) = \left.\frac{d^2\sigma}{dt\, dM}\right|_{\substack{t=0 \\ m=m_\varrho}} \frac{1}{2} \pi \Gamma_\varrho ,$$

where $d^2\sigma/dt\,dM$ comes from the phenomenological Söding fit to their data using $m_\varrho = 770$ MeV and $\Gamma_\varrho = 150$ MeV. The energy dependence of the Φ photoproduction cross section has been read off from the data in ref. (10). The errors attached in the text to the above quantities, added as further degrees of freedom to our fit, include errors quoted by the authors (refs. (7, 9, 10)) and normalization uncertainties in our experiment. The errors attached to m_ϱ, m_ω, and m_Φ are a pessimistic estimate of systematic incertitudes in the mass reconstruction.

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