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THE "REAL" AND "IMAGINARY" PARTS OF THE INCONSISTENCY IN ρ^0-ω INTERFERENCE

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ABSTRACT

The current status of experiments implying a G parity violating $\omega \to 2\pi$ decay by virtue of an observed ω-ρ^0 interference is discussed. Some appreciable part of the apparent inconsistencies in the various sets of data can be trivially removed. The possibility of real inconsistency between different experiments, and between experiments and theory, leads to the need for specific experiments to resolve the difficulties.

I. INTRODUCTORY REMARKS

We're all familiar with the situation in experimental physics in which the first few independent measurements of some quantity disagree, then finally converge to a stable answer. The ρ^0-ω interference problem seems to be an inversion of this process. Consider the announced preliminary results of the Berkeley and Orsay groups (at Argonne last spring) of the interference effect in the $\pi^+\pi^-$ spectrum:

Berkeley: $\dfrac{\omega \to 2\pi}{\omega \to 3\pi}$ = a few % and 195 ± 20 deg total relative phase;

Orsay: $\dfrac{\omega \to 2\pi}{\omega \to 3\pi}$ = a few % and 195 ± 30 deg total relative phase.

Or consider the ratio of the partial width for leptonic decay of ρ^0 found by photoproduction to that found by colliding beams:

$$\frac{\Gamma_\rho \to \ell^+\ell^- \text{ (photoproduction)}}{\Gamma_\rho \to \ell^+\ell^- \text{ (colliding beams)}} \approx 1.2 \pm 0.2$$

We'll see that these "agreements" turn into dilemmas (and perhaps back again!). The types of questions we need to answer are

(a) Should the $\pi^+\pi^-$ spectra look alike in different experiments?

(b) Should the $\ell^+\ell^-$ spectra similarly look alike (leading to equal $\Gamma_\rho \to \ell^+\ell^-$)?

(c) Should the ρ look the same width in experiments unable to resolve details of interference?

All of these can be generally included in the rather ambitious question

(d) Are all experiments on $\rho^0\omega$ interference mutually consistent and consistent with theory?

II. THEORY

We will not belabor any fundamentals here, but try to present the theoretical conclusions of investigators having slightly varying viewpoints.

The first-generation papers[1] on ρ^0-ω inteference (1965) pointed out that it could occur in a number of reactions, and made estimates of the size of the effect

$$\frac{\omega \to \pi^+\pi^-}{\omega \to 3\pi} \approx 1\%.$$

The second-generation papers[2] (1969) made explicit parameterizations of the effect, including phase, and that by A. Goldhaber et al. pushed the assumptions to the limit that all parameters were determined by theory for a variety of experiments.

Third-generation papers[3] (1970) appear to require considerably more parameters, throwing conclusions based on the above into doubt.

We'll come back to this later.

A. Elements of the Parameterization (1969)

Figure 1 shows the magnitude and phase parameters attached to each kind of vertex that might enter into processes we will consider. Using the propagators for internal lines, we can make each amplitude (for $V = \rho^0$ or ω) by compounding the appropriate factors. Since we'll always be adding a ρ^0 amplitude to an ω amplitude, we let β represent the phase of the vertex for ω relative to that for ρ. Also note that if some other strong process than $\pi^+ p \to V^0 \Delta^{++}$ is used, another β'_{SI} must be introduced.

B. Examples of Above Parameterization

The three major experiments giving phase information:

Leptonic decay of ρ^0 photoproduced off carbon. If we break up the photoproduction as shown in Fig. 2a, and make no assumptions about time-reversal invariance at the γ-V vertex, the relative magnitude and phase of the interference term (at m_ω, with $m_\omega \approx m_\rho$ and $\Gamma_\omega \ll \Gamma_\rho$) will be

$$\frac{g_\omega}{g_\rho} \frac{\Gamma_\rho}{\Gamma_\omega} \frac{a_\omega g'_\omega}{a_\rho g'_\rho} \exp\left[i(\beta_{em} + \beta_P + \beta'_{em}\right],$$

where the primes indicate the vertex under time reversal. (Smaller terms from the g-parity violating vertex letting $\rho \leftrightarrow \omega$ will also be present. These have been neglected. The main reason to consider these leptonic modes is to see if they give additional information on processes in which the g-violating vertex dominates.)

Production of $\pi^+\pi^-$ from e^+e^- annihilation (Fig. 2b). Under assumptions similar to those in 1, we get

$$\frac{g_\omega}{g_\rho} \frac{\Gamma_\rho}{\Gamma_\omega} \frac{\delta}{\Gamma_\rho/2} \exp\left[i(\beta_{em} + \beta_D)\right].$$

Production of $\pi^+\pi^-\Delta^{++}$ from $\pi^+ p$ (Fig. 2c). Similarly, we get

$$\frac{A_\omega}{A_\rho}\left(\frac{\Gamma_\rho}{\Gamma_\omega}\right)\frac{\delta}{\Gamma_2/2}\exp\left[i(\beta_{SI}+\beta_D)\right].$$

C. Theoretical Estimates for Parameters

All theories assume that the SU(6) vector dominance prediction

$$\frac{g_\omega}{g_\rho} \approx \frac{1}{3}, \quad \beta_{em} = 0,$$

will be approximately valid. The phase appears to be even more fundamental that SU(6), as it would follow from time reversal (if assumed) for stable ρ and ω (as with Horn).

The π-B exchange degeneracy argument of A. Goldhaber et al. predicts $\beta_{SI} = \pi/2$ for π^+p, $-\pi/2$ for π^-p, and some other results. The magnitude of the production amplitudes, A_ω/A_ρ, is taken to be 0.5 for the π^+p experiment (using $\omega \to 3\pi$, $\rho \to 2\pi$).

The theorists (1969) generally agree that if one can neglect the ordinary electromagnetic diagrams contributing to $\omega \to 2\pi$--such as Fig. 2d, which can be roughly calculated and come out small compared with the $\approx$ 1% branching ratio--then unitarity and ρ-dominance of the $\pi\pi$ amplitude imply

$$\beta_D = \arg(\text{Breit-Wigner for } \rho),$$

or, in particular, near the ω mass,

$$\beta_D \approx 90 \text{ deg.}$$

The magnitude of the vertex δ is then attributable to an unknown process, and can be phenomenologically derived (A. Goldhaber et al.) or calculated (via scalar mesons in "tadpole" diagrams, as in Coleman and Glashow). These results all lead to a ratio $\frac{\omega \to 2\pi}{\omega \to 3\pi}$ of a few percent. Our δ = 3 MeV corresponds to $\approx$ 2.5%, a value near that phenomenologically determined.

Finally, we need estimates of the parameters involved in photoproduction processes. If the process (off complex nuclei) is diffractive for both ρ and ω, then $\beta_P = 0$. The ρ production looks consistent with pure diffraction, but ω production is less well known, so $\beta_P = 0$ is not very reliable. Empirically it appears $a_\omega \approx a_\rho$.

D. Prediction for the Major Experiments

Substituting the above values we get,

for $e^+e^- \to \pi^+\pi^-$,

$$\frac{1}{3} \times 10 \times \frac{3}{120/2} e^{i(0+90)} = 16\% \text{ relative effect in amplitude with phase 90 deg;}$$

for $\pi^+p \to \Delta^{++}\pi^+\pi^-$

$$\frac{1}{2} \times 10 \times \frac{3}{120/2} e^{i(90+90)} = 25\% \text{ relative effect with phase 180 deg;}$$

for $\gamma C \to C\ell^+\ell^-$

$$\frac{1}{3} \times 10 \times 1 \times \frac{1}{3} e^{i(0+0+0)} \approx 100\% \text{ relative effect with phase 0 deg.}$$

Horn has pointed out that the interference in this last reaction is such a large effect that all calculations must be carried out to another order beyond that for those processes involving only the G-parity-violating vertex. He claims that the total relative amplitude can then have an imaginary part up to $\approx 1/3$ that of the real part, corresponding to phases such as 20, 160, 200, and 340 deg for the sum

$$\beta_{em} + \beta'_{em} + \beta_P \equiv \beta_T .$$

E. Getting β_T from Leptonic Decays

Since until recently the experiments on leptonic decay were not sensitive to fine structure (and hence not a direct phase determination), several authors[4] developed formulae for

$$R = \frac{\Gamma_{\rho \quad \ell^+\ell^-} \text{(photoproduction)}}{\Gamma_{\rho \quad \ell^+\ell^-} \text{(colliding beams)}},$$

with the observation that the rate (integrated area under the spectrum) would be different for different total phases. The denominator was taken as derived from a colliding-beam experiment involving only pure ρ^0. We now know that this must be modified for interference with the ω, but since the expected interference effect in photoproduction is larger by a factor of 6, the published results do not change much. The results imply a numerically explicit form

$$R \approx f(\beta_{total}) ,$$

which is, however, double-valued. This is shown in Fig. 3.

III. EXPERIMENTS

A quick summary of available experiments indicates that only a few published ones offer phase information at this point. We quote total relative phases (avoiding theoretical biases at this time).

A. CEA-DESY-Orsay

(Photoproduction of $\ell^+\ell^-$ and production of $\pi^+\pi^-$ from e^+e^- annihilation.[5]) The determination of the R as given above is 1.17 ± 0.2. This gives

$$\beta_{em} + \beta'_{em} + \beta_P = 130 \pm 30 \text{ deg} \quad (\approx 160\text{-deg theory is closest}).$$
$$\text{or } 260 \pm 30 \text{ deg}$$

There are two experiments measuring leptonic ρ decay from strongly produced ρ,[6] but no phase information was deduced from them. There are also new high resolution results from DESY and Daresbury[7] on the photoproduced $\rho \to e^+e^-$, but at present these data support different values of β_{total}, namely, about 20 deg and 70 deg respectively.

B. Berkeley

Two groups at Berkeley[8] have performed $\pi^+p \to \Delta^{++}\pi^+\pi^-$, and the combined result will be seen in Fig. 6 (upper left). (Combination is justified because beam, incident momentum, chamber, and measuring machines were identical.) The phase information is

$$\beta_{SI} + \beta_D = 190 \pm 17 \text{ deg} \qquad (180\text{-deg theory}).$$

On the scale shown, the effect should be mainly in one bin. Although not justified by the resolution, finer bins are shown in Fig. 4 for completeness. A great deal of fitting with different assumptions about mass calibration, coherence, etc., failed to change the phase result given. Rho's produced by alternative mechanisms, such as π^-p (Selove, Blumenfeld, and Wenzel) or by K^-p (Flatté[9]) see hints of peaking at ω mass, but the π^-p results are still too preliminary to quote,

and no phase information has been extracted on the K^-p work. A $p\bar{p}$ annihilation result[10] will soon be released, and those data will be shown later in this note.

C. Orsay

The Orsay group[11] has reported fitted data as shown in Fig. 5 (solid line), giving

$$(\beta_{em} + \beta_D)_{Orsay} = 195 \pm 28 \text{ deg.}$$

There is a trivial difference in notation (the Orsay group's propagators have poles of opposite sign to those in the theoretical papers) which is equivalent to

$$\beta_{em} + \beta_D = 360 \text{ deg} - (\beta_{em} + \beta_D)_{Orsay} = 165 \pm 28 \text{ deg}$$
(90-deg theory).

Thus a slight problem has appeared. If we relinquish the absolute normalization, the fit is basically the same, and if we force $\beta_{em} + \beta_D = 90$ deg as theory would have it, the fit looks rather poor (Fig. 5, dotted line), since the normalization is deemed to be 30% off and the fit still has problems with the peak points. If, however, we let everything, including the mass calibration, go free, a new and slightly better χ^2 minimum appears very close to the theoretical solution ($\beta_{em} + \beta_D = 109 \pm 14$ deg), with a fairly wide ρ ($\Gamma_\rho = 145$ MeV) almost degenerate with the ω. (See Fig. 5, dashed line.) It is difficult to justify this fit, since the mass calibration would have to be ≈ 5 MeV off, and the Orsay claim of $\pm$ 1 MeV looks well founded. This result, however, illustrates how critical the fits are to mass calibration, and how a wide ρ seems to be accommodated even in colliding-beam data. (More on this later.)

IV. CONSISTENCY

A. Leptonic Modes

Whether one assumes time-reversal invariance and gets

$$\beta_P = 130 \pm 30 \text{ deg} \quad \text{or } 260 \pm 30 \text{ deg}$$

(or the corresponding updated results of DESY or Daresbury),

or one stays with the general

$$\beta_{em} + \beta'_{em} + \beta_P = 130 \pm 30 \text{ deg} \quad \text{or } 260 \pm 30 \text{ deg},$$

this result decouples from the rest of the reactions, since no information about β_{em} is forthcoming in either case. This might not be true if in the future β'_{em} is measured not in additive combination with β_{em}. The old result for the total phase agrees with one of the four approximate possibilities suggested by Horn, but the new results indicate a still uncertain physical value.

B. Simultaneous Fitting of Remainder of Data

With a common δ, m_ρ, Γ_ρ but different phases, we attempt to simultaneously fit the Berkeley, Orsay, and Argonne data with models as used by the individual experimenters. Also included is a $\pi^+\pi^0$ system removed from N^* interferences (so it should be a pure ρ^+) and the $\pi^+\pi^-$ from A_2^+ (subtracted) $\rightarrow \pi^+\pi^+\pi^-$. The latter two sets are from the Berkeley data. Figure 6 shows that this procedure converges on something close to the theoretical solution. (Note the phase chart, which gives the production phase, and also gives this phase plus the theoretical 100-deg decay phase. This sum is the fitted total phase which really determines the pattern.) However, the confidence level $\approx$ 1% for the fit is poor. The Orsay data are especially poorly fitted. If we impose $\Gamma_\rho = 145$, $m_\rho = 782$ on this system (it fits the Orsay data alone not too badly), the fit degenerates because the other data are not consistent with such a high ρ mass (Fig. 7). Our conclusion is that interference effects are not solely responsible for the differences of the $\pi\pi$ spectrum seen in different experiments. Since other mechanisms have been postulated[13], this is not too surprising.

C. Individual Fitting Consistency

If we ignore the problems above and simply take each experimenter's best values, we find a problem between Berkeley and Orsay. Namely, if $\beta_{em} = 0$,

$$\beta_{SI} = 25 \pm 33 \text{ deg} \qquad \text{(90-deg theory)},$$

$$\beta_D = 165 \pm 28 \text{ deg} \qquad \text{(90-deg theory)},$$

but if $\beta_{em} = 65$ deg (arbitrarily),

$$\beta_{SI} = 90 \pm 33 \text{ deg} \qquad \text{(90-deg theory)},$$

$$\beta_D = 100 \pm 28 \text{ deg} \qquad \text{(90-deg theory)},$$

However, $\beta_{em} \neq 0$ is frowned upon, so one is temped to stretch the errors and say that the "real part" of the inconsistency equals 0.

Suppose, however, we consider the fantasy that these results hold up. What will that imply? Let us construct (Fig. 8) a truth table (which aids in examining the logical interrelations) for the statements (i) $\beta_{em} + \beta_D \approx \pi$, (ii) $\beta_{SI} + \beta_D \approx \pi$, (iii) π-B exchange degeneracy, (iv) T invariance and vector dominance, (v) Unitarity, ρ dominance of $\pi\pi$, δ-dominant contributing vertex to $\omega \to \pi\pi$. The table assigns T (true) to a given statement, and then lists all consistent combination of T, F for the other statements. If a statement can consistently be either T or F, only the T combination has been entered (in keeping with the principle of assumed innocence). As expected, no row has all T's. One can put in his own a priori values on these statements, but it is interesting to pick the rows with a single F. Then we have only two:

Either $\beta_{em} + \beta_D \neq \pi$, if the Orsay result holds up, $\beta_{em} \neq 0$.

If this has an unacceptable taste, then one must accept the idea that two or more of the statements (i) through (v) are false.

Reminding ourselves that these conjectures rest on preliminary experiments in this field, let us look at what may turn out to be the flaw in all of this reasoning.

D. Third-Generation Theories

Sachs[3] has pointed out that considering the problem of the G-parity violation as a result of mass mixing alone leaves out a number of parameters. Rather than

$$M = \begin{pmatrix} m_\rho - m - i(\Gamma_\rho/2) & \delta \\ \delta & m_\omega - m - i(\Gamma_\omega/2) \end{pmatrix}$$

he would use (effectively)

$$M' + i\Gamma'/2,$$

where M' and Γ' are real nondiagonal matrices. This seems to be equivalent to using a complex δ, and since we use $\delta \exp(i\beta_{SI})$ for the G-parity-violating vertex, the parameterization is still adequate for fitting purposes. However, the physical meaning and predictions for δ, β_{SI}, and β_D would change. Indeed, in Sachs' formulation the number of parameters is such that no definite prediction is available. He finds, however, that the Berkeley and Orsay results become consistent if a number of undetermined but limited parameters are allowed to take on their extrema and if the data errors are used to "reach down" to these values of the parameters. What seems fortuitous to the theoretician seems suspicious to the experimentalist.

The parameterization seems to be equivalent to that by Horn, (a one-to-one correspondence has not been shown), allowing complex δ, where the tentative conclusion was that A. Goldhaber et al. were justified in specializing $\delta \exp(i\beta_{SI})$ to $\approx 3 \exp(i90 \text{ deg})$ if the arguments (iii) and (v) were correct. Thus it appears that the Sachs result does not alter the logic presented in this note. It does present evidence (albeit meager) that the Berkeley-Orsay inconsistency arises because theoretical statements (iii) and (v) are both false.

V. PROPOSED EXPERIMENTS

A. Repeats

As usual, all experiments should be done again with better statistics, better resolution, and careful attention to mass calibration. In particular, more precise data on $\gamma + C \rightarrow C + \pi^+\pi^-$, not mentioned above because the old data were both limited and of poor resolution and not useful for phase determinations, should show interference effects of

relative size

$$\frac{g_\omega}{g_\rho}\,\frac{a_\omega}{a_\rho}\,\frac{\delta}{\Gamma_\rho/2}\,\frac{\Gamma_\rho}{\Gamma_\omega}\,\exp\left[i(\beta_{em}+\beta_P+\beta_D)\right. \approx \frac{1}{3}\times 1\times\frac{3}{120/2}\,\frac{120}{12}\,e^{i(0+(0\text{ or }\neq 0)+90)}\Big]$$

$\approx$ 16% with phase 90 deg (like the prediction for Orsay),

or, if $\beta_P \neq 0$, a phase differing from that expected for Orsay by β_P.

B. New Experiments

Reactions such as $\pi^+ p \to \ell^+\ell^-\Delta^{++}$ will presumably measure

$$\frac{A_\omega}{A_\rho}\,\frac{\Gamma_\rho}{\Gamma_\pi}\,\frac{g'_\omega}{g'_\rho}\,\exp\left[i(\beta_{SI}+\beta'_{em})\right] \approx \frac{1}{2}\times\frac{120}{12}\times\frac{1}{3}\exp\left[i(\beta_{SI}+0)\right],$$

again a 100%-type effect but also sensitive to β_{SI}. Although difficult this fascinating reaction may also give information about the time-reversed phase β'_{em}.

C. Far-Out Experiments

If the proposed Macek-Maglić $\pi\pi$ colliding-beam machine[12] is built (at the Los Alamos π factory), the $\pi^+\pi^-$ spectrum should exhibit a clean ρ^0, since the interference is from the sum shown in Fig. 9, or is

$$\frac{\delta}{\Gamma_\rho/2}\times\frac{\Gamma_\rho}{\Gamma_\omega}\times\frac{\delta}{\Gamma_\rho/2}\exp\left[i(\beta_D+\beta'_D)\right] \approx \frac{3}{60}\times 10\times\frac{3}{60}\,e^{i0} = 2.5\%,\ \text{relative phase } 0,$$

and the ω peak in the interference is negligible If the count rate would ever render it feasible, the reaction $\pi^+\pi^- \to e^+e^-$ would measure

$$(\text{time reversal})\,(e^+e^- \to \pi^+\pi^-),$$

and the interference pattern would be a phase-sensitive test of T in electromagnetic interactions, the result to be compared that seen at Orsay.

VI. CONCLUSIONS

The trivial disagreements arising from conventions (signs of poles, factoring out ρ propagator) have been removed. There remains a curious but contested result (effective $\beta_P \neq 0$) for lepton decay of photoproduced ρ. There also remains an inconsistency between Berkeley and Orsay in the presence of three theoretical assumptions. One can get out of the difficulty by having the experiments change by a total of ≈ 2 standard deviations, or by relinquishing one or more of the theoretical statements. There is a slight indication, if both experimental values are close to truth, that more than one theoretical argument will fall. Irrespective of the theory, however, all available data are not simultaneously well fitted by a single ρ mass and width, indicating other effects in this subtle particle mixture.

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Note added subsequently: While this report was in preparation, some of the results referred to in the text have been announced, though not published. In particular, the data of Hagopian et al.,[4] from $\pi^- p \to \pi^- \pi^+ n$ (at 2.3 GeV/c) shows a strong peaking effect at the mass of the ω in the $\pi^-\pi^+$ distribution [for $0.06 \to t \to 0.24\,(\mathrm{MeV/c})^2$]. The reaction $\pi^+ n \to \pi^+ \pi^- p$ as measured by Katz et al.[15] shows some evidence for a dip at the ω mass. In terms of our logical analysis, we would have to introduce (possibly) new production phase angles for each of these, and the total ω-ρ relative phase would be $\beta_{SI}(\pi^-\rho) + \beta_D$

and $\beta_{SI}(\pi^+ n) + \beta_D$ respectively.

A. Goldhaber et al.[2] have pointed out that isospin invariance alone, without reference to a particular production mechanism, gives the constraint $\beta_{SI}(\pi^- \rho) = \beta_{SI}(\pi^+ n) - \pi$. G. Goldhaber[16] has noted that the experimental determination of the quantities $\beta_{SI} + \beta_D$ for each of the above reactions is redundant in that they must satisfy this consistency check – i.e., the sign of the interference term must reverse. At this early stage we will not attempt fits to the unpublished data, but it is clear that the peak and dip imply

$$\beta_{SI}(\pi^- \rho) + \beta_D \approx 0$$

$$\beta_{SI}(\pi^+ n) + \beta_D \approx \pi$$

These results are self-consistent and since $\beta_{SI}(\pi^+ n)$ is predicted[2] to be the same as for the Berkeley experiment, this lends weight to the correctness of that result and the implications thereof.

REFERENCES

1. J. Bernstein and G. Feinberg, Nuovo Cimento 25, 1343 (1962); S. Coleman and S. Glashow, Phys. Rev. Letters 6, 423 (1961); J. Harte and R. G. Sachs, Phys. Rev. 135, B459 (1964); J. Yellin, Phys. Rev. 147, 1080 (1966); S. Coleman, S. Glashow, H. Schnitzer, and R. Socolov, in Proceedings of the Twelfth International Conference on High-Energy Physics, Dubna, U.S.S.R., 1964, Vol. I, p. 785.
2. D. Horn, CalTech preprint CALT-68-225; M. Gourdin, L. Stodolsky, F. Renard, Laboratoire de Physique Théorique et Hautes Energies, Orsay, Report LPTHE/69/58, Aug. 1969; A. S. Goldhaber, G. Fox, and C. Quigg, Phys. Letters 30B, 249 (1969).
3. R. G. Sachs and J. Willemsen, Enrico Fermi Institute, Chicago, Report EFI 69-102, Dec. 1969.

4. M. Davier, Phys. Letters 27B, 27 (1968); R. Parsons and R. Weinstein, Phys. Rev. Letters 20, 1314 (1968); G. Greenhut and R. Weinstein, Center for Particle Theory, Austin Report CPT-17, July 1969.
5. J. de Pagter et al., Phys. Rev. Letters 16, 35 (1966); J. Asbury et al., Phys. Rev. Letters 19, 869 (1967); P. Rothwell et al., Phys. Rev. Letters 23, 1521 (1969); J. Augustin et al., Phys. Letters 28B, 508, 513, 517 (1969); V. Auslander et al., Yadern. Fiz. 9, 114 (1969).
6. A. Wehmann et al., Phys. Rev. Letters 17, 1113 (1966); 18, 929 (1967); B. Hyams et al., Phys. Letters 24B, 634 (1967).
7. See Proceedings of the Daresbury Conference on Electromagnetic Interactions (unpublished).
8. G. Goldhaber et al., Phys. Rev. Letters 23, 1351 (1969); G. Gidal et al., (Lawrence Radiation Laboratory), private communication.
9. S. Flatté et al., Phys. Rev. 145, 1050 (1966); Phys. Rev. 155, 1517 (1967); Lawrence Radiation Laboratory Report UCRL-18689.
10. W. Allison et al., ρ -ω Interference in Antiproton Annihilations, Argonne National Laboratory Preprint.
11. J. Augustine et al., Nuovo Cimento Letters 2, 214 (1969).
12. R. Macek et al. Princeton-Penn Accelerator Report 14 (University of Pennsylvania, Philadelphia).
13. M. Einhorn, Phys. Rev. 185, 1960 (1969).
14. S. Hagopian (Florida State University), private communication, 1970.
15. P. Katz et al., Bull. Am. Phys. Soc. 15, 69 EG7 (1970).
16. G. Goldhaber (Lawrence Radiation Laboratory), private communication, 1970.

FIGURE LEGENDS

Fig. 1. Parameterization of the amplitude and relative phase of individual vertices. V = either ρ or ω; β = phase of vertex for ω relative to the phase of the same vertex for ρ (i.e., for diagrams with a V, only one β exists, and it relates V = ω to V = ρ).

Fig. 2. Processes exhibiting ρ-ω interference.

Fig. 3. Lepton pair-production ratio as a function of β_{total}. The experimental result for R and its error are given by the cross-hatched band.

Fig. 4. The $\pi^+\pi^-$ mass spectrum for the reaction $\pi^+p \rightarrow \Delta^{++}\pi^+\pi^-$. The top figure shows in detail the interference region of the complete spectrum shown in the bottom figure. Both scales are in MeV.

Fig. 5. The $\pi^+\pi^-$ mass spectrum for the reaction $e^+e^- \rightarrow \pi^+\pi^-$. Solid line is the fit by the Orsay experimenters. Dotted line is our fit with normalization free but phase fixed. Dashed line is our fit with everything free including ω mass. The difference between the location m_ω and m'_ω is the effective shift in mass calibration necessary to accommodate this last fit.

Fig. 6. Simultaneous fitting of the $\pi^+\pi^-$ mass spectrum from a variety of reactions (Γ_ρ, m_ρ free). Here ∂ means degrees of freedom. The values of the parameters are given at upper right. The data are from the sources marked on each graph, where the momentum of the incident particle follows the reaction. Data at 3.8 GeV/c are from the Berkeley experiment. Backgrounds are shown with a dashed line. At lower right a phase diagram gives the total ω-ρ phase for each reaction at $m_{\pi\pi} = m_\omega$ (marked by an arrow and coded to match the corresponding plot). About 90 deg earlier in phase on the diagram is shown the portion of this total phase arising from the production process (marked by an appropriate $\beta_{production}$) on the assumption that the unitarity argument in the text holds. The small figures near the points 0, 90, 180, and 270 deg show what the interference term will look like for these

values of the total phase $\beta_{production} + \beta_D$. Errors on the total phase appear on the boundary of the circle, and also apply to the value of the production phase.

Fig. 7. Same as Fig. 6, except (Γ_ρ, m_ρ fixed).

Fig. 8. Truth table for the consistency of theory and experiment on ρ-ω interference.

Fig. 9. Interference terms for a $\pi^+\pi^-$ colliding-beam experiment (amplitudes pertinent to ρ^0-ω interference in $\pi^+\pi^- \rightarrow \pi^+\pi^-$).

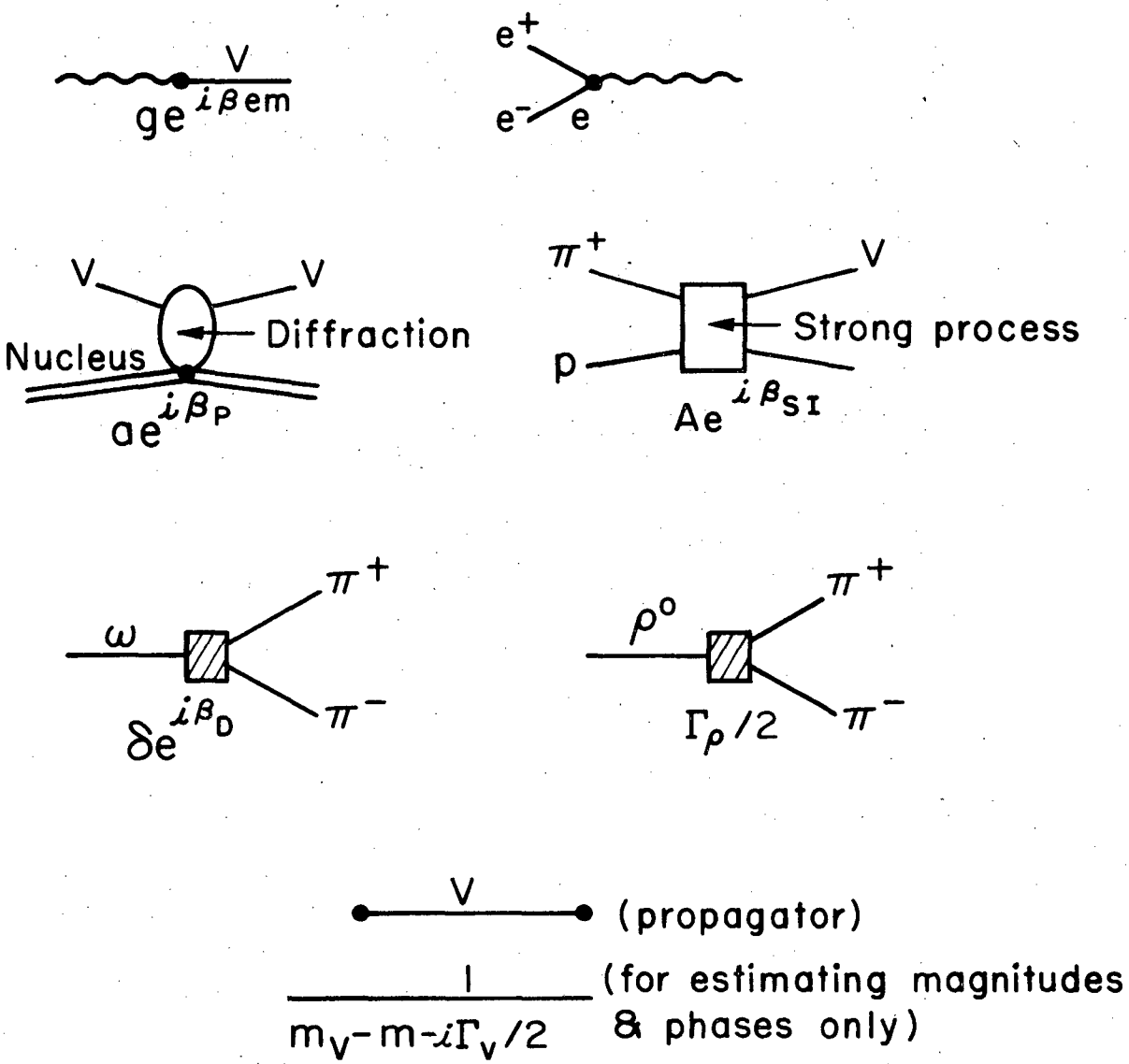

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Fig. 1

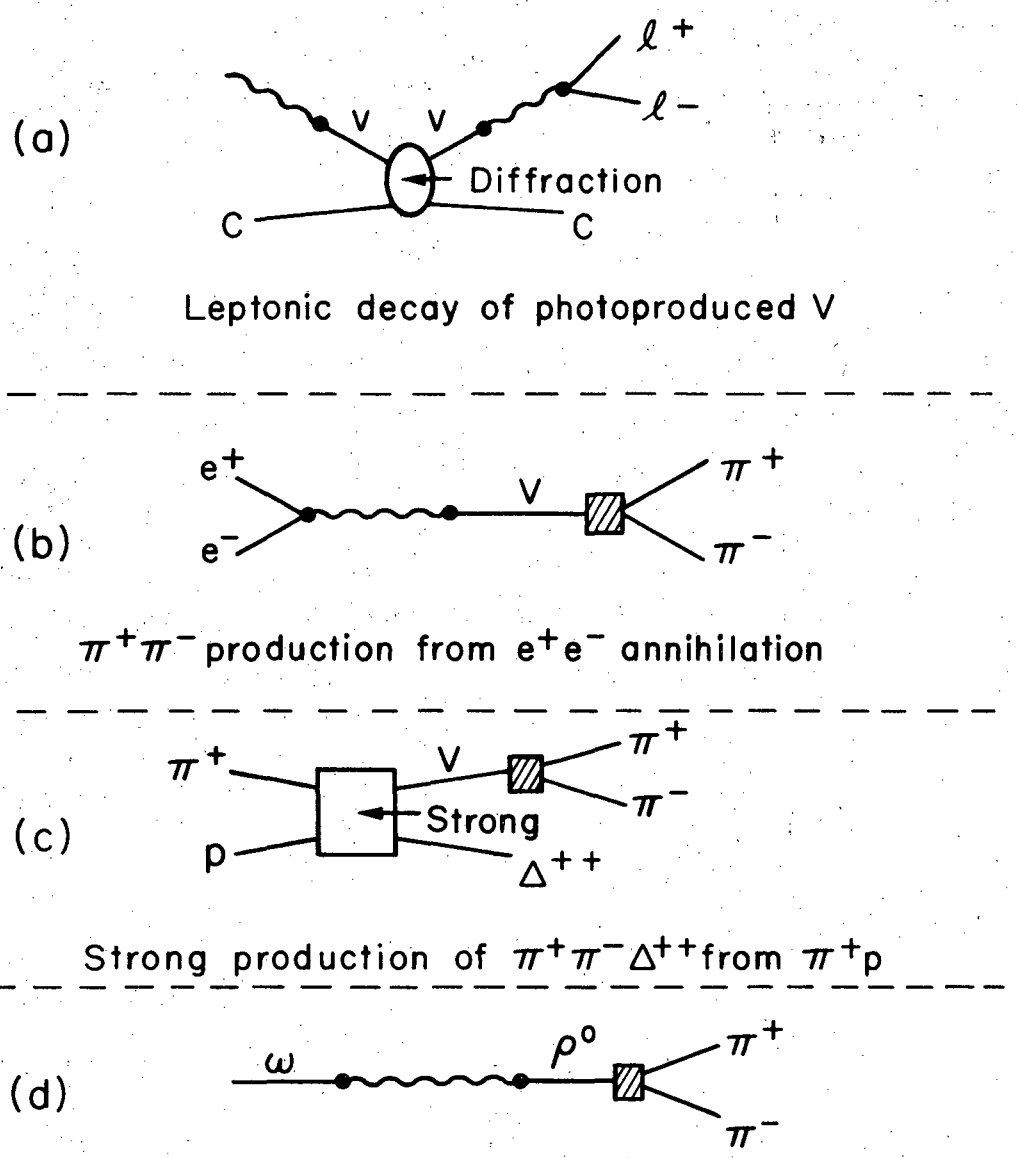

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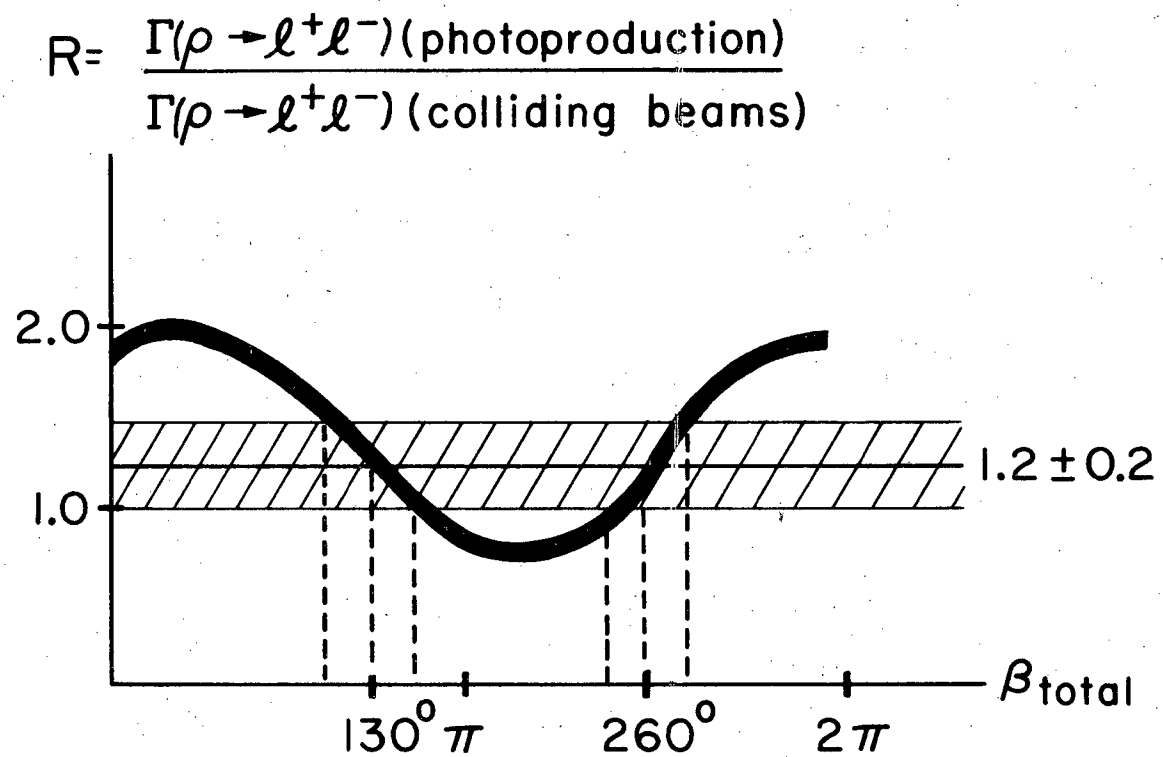
Fig. 2



XBL701-2134

Fig. 3

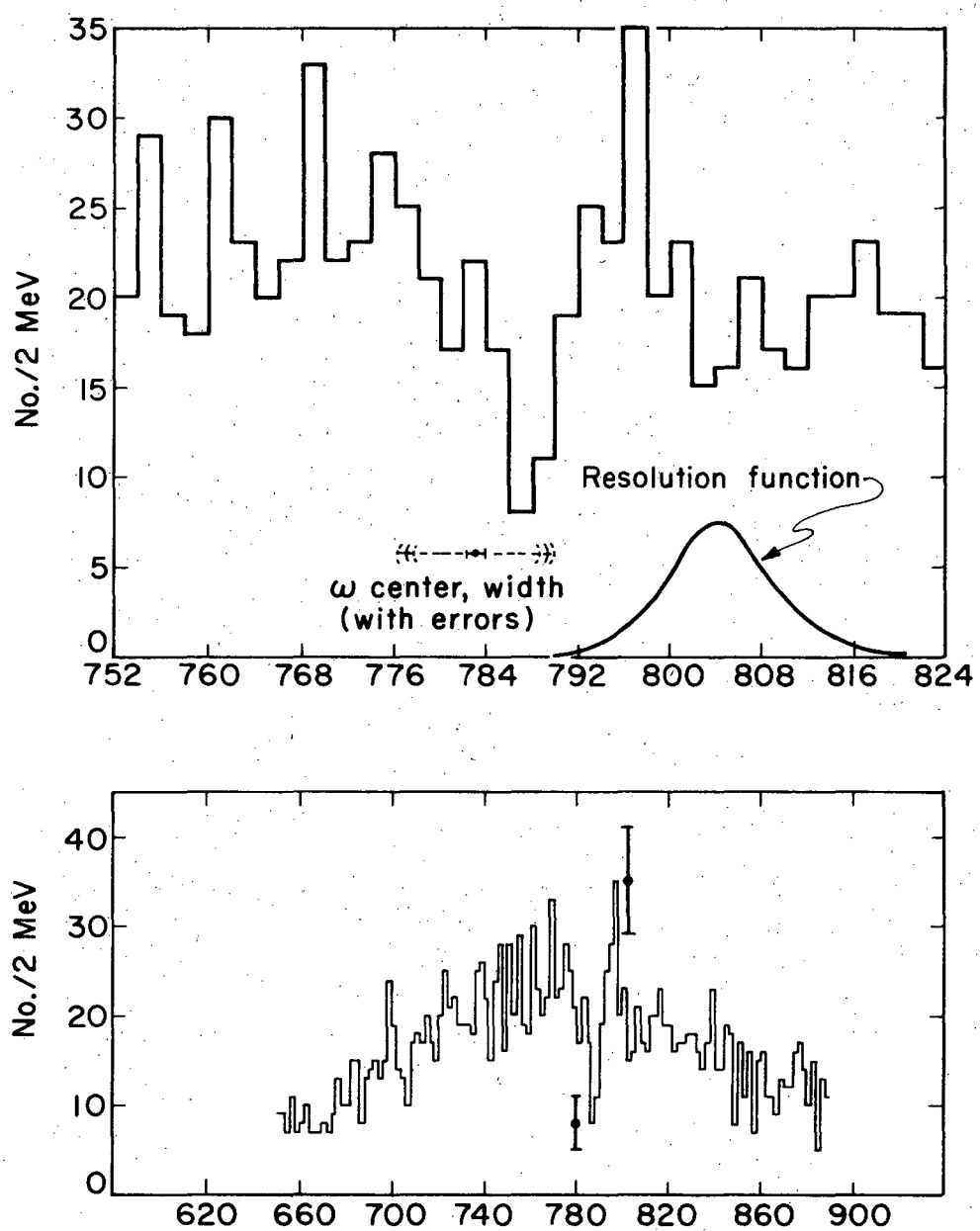


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Fig. 4

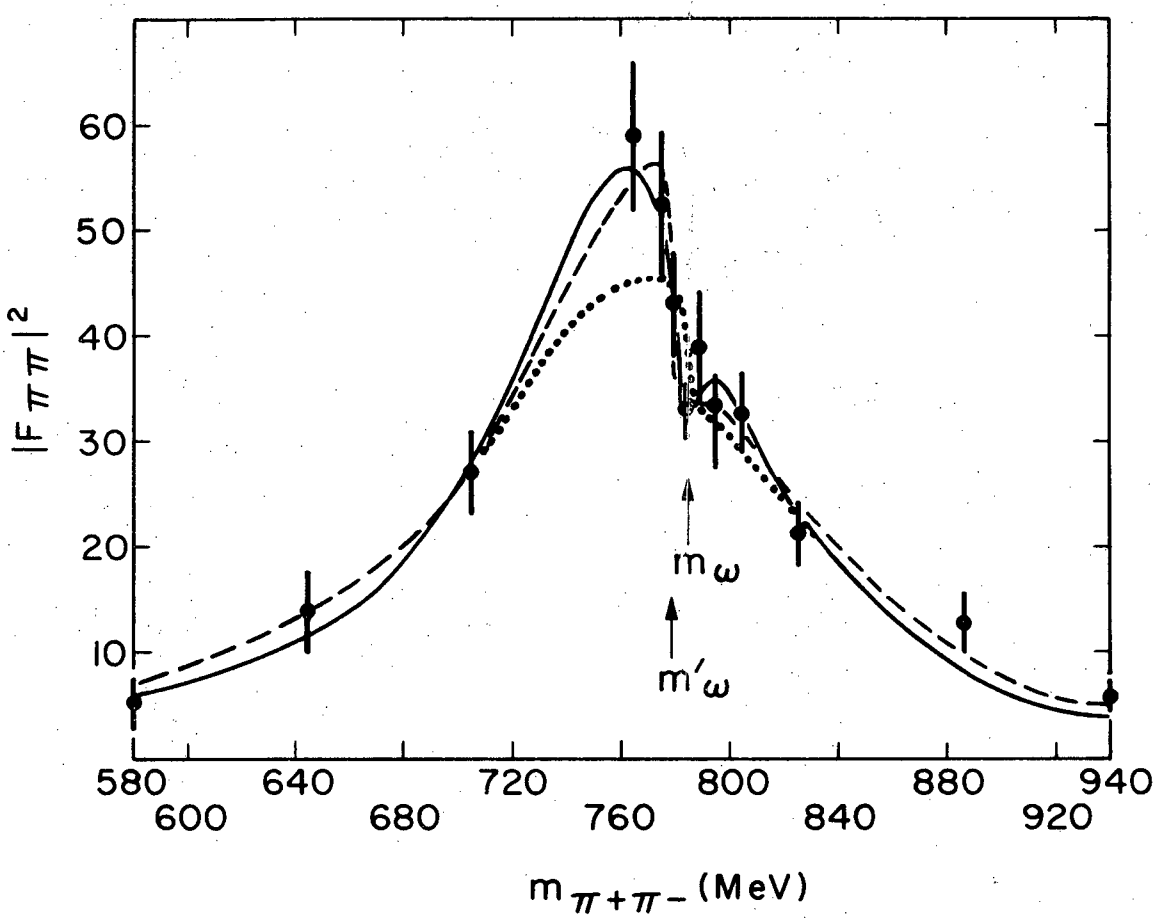

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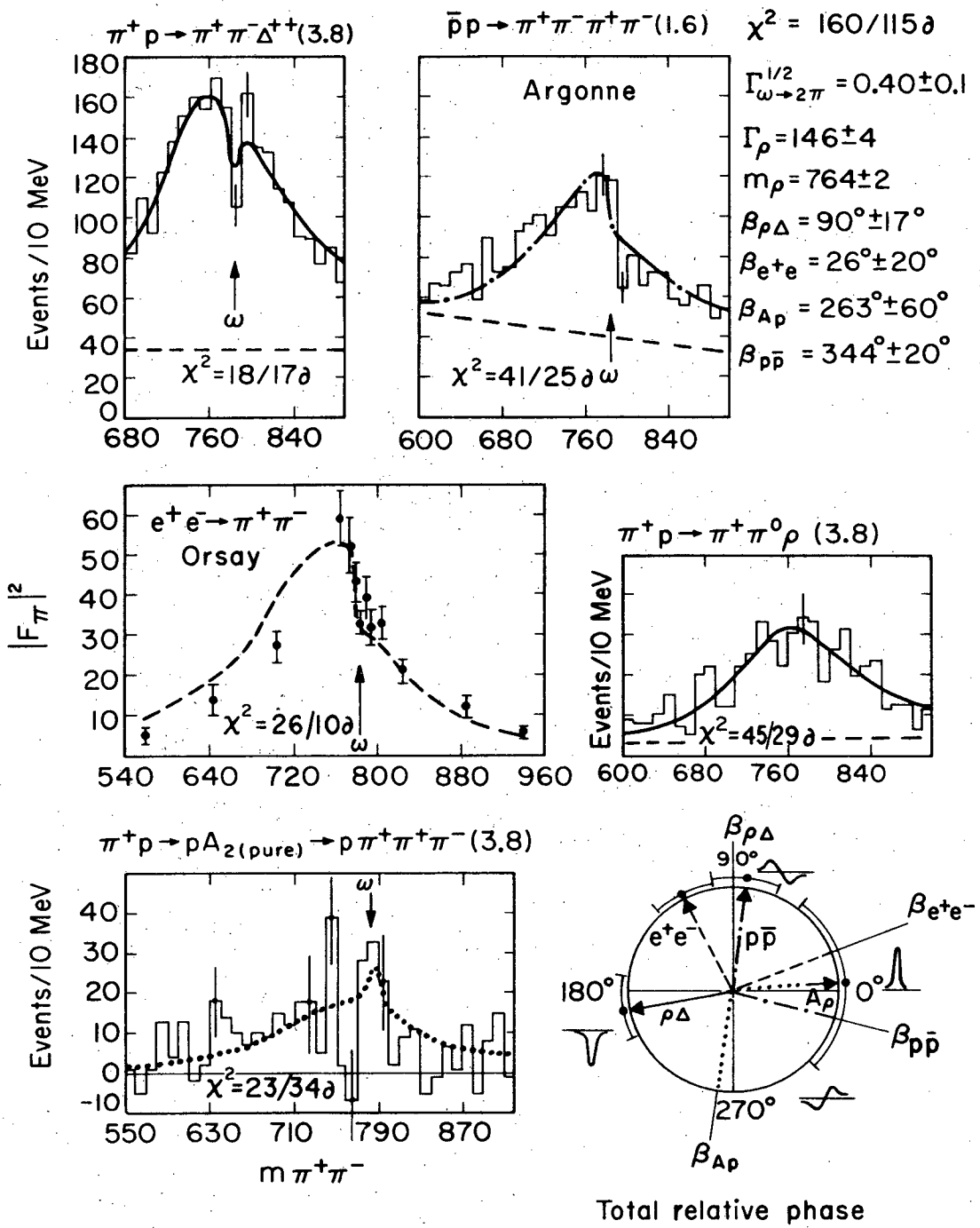
Fig. 5



XBL701-2133

Fig. 6

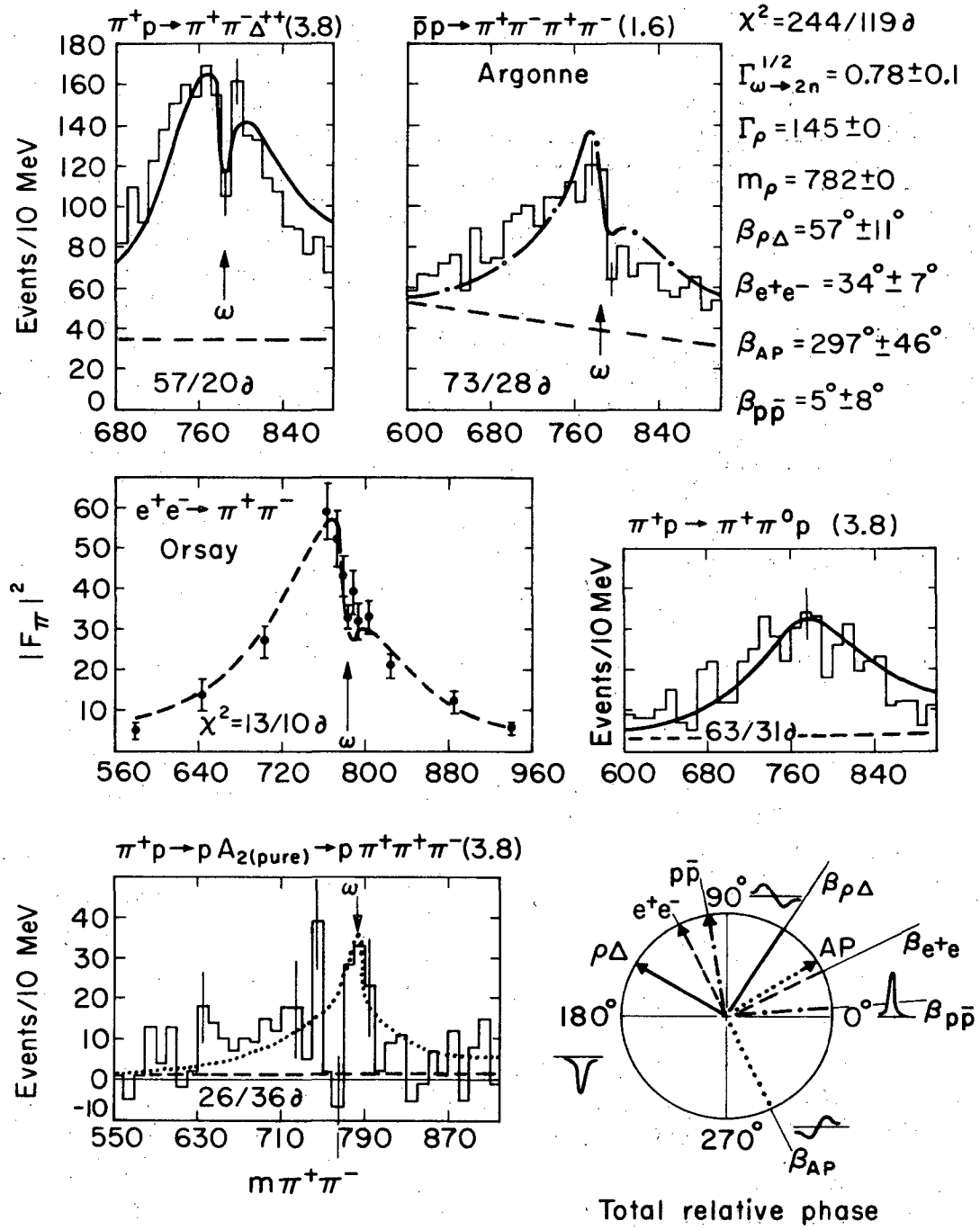


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Fig. 7

	Experiment		Theory		
No.	Orsay $\beta_{em}+\beta_D \approx \pi$	Berkeley $\beta_{SI}+\beta_D \approx \pi$	π-B exch'g degen'cy	T invariance (vector dominance)	$\frac{\omega \to 2\pi}{\omega \to 3\pi} \sim 1\%$ + Unitarity + ρ dom.
1	T	T	T	F	T
2	T	T	F	T	F
3	F	T	T	T	T
4	T	F	F	F	T
5	T	F	T	T	F
6	F	F	F	T	T
7	F	F	T	T	F

(If can be simultaneously T or F consistent with other choices, take T)

<u>Most likely</u>(?) $\begin{cases} \beta_{em} \neq 0 \\ \quad \underline{\text{or}} \\ \beta_{em} + \beta \neq \sim \pi \end{cases}$

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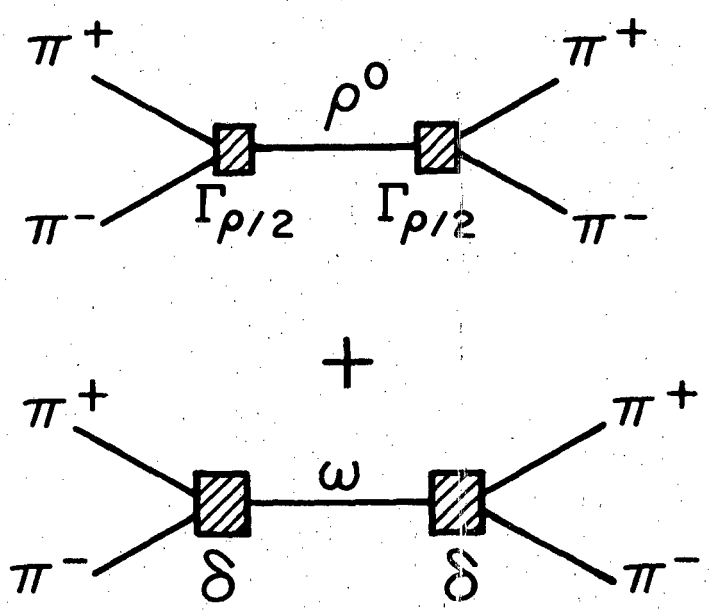
Fig. 8



Amplitudes pertinent to $\rho^0-\omega$
Interference in $\pi^+\pi^- \to \pi^+\pi^-$

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Fig. 9

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