ANALYSIS OF $\pi\rho$ ENHANCEMENTS IN $\pi^- + d$ INTERACTIONS AT 3.2 BeV/c*

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In a study of multipion final states produced in π^+p interactions at 3.65 BeV/c, Goldhaber et al.[1] demonstrated that almost all $p\pi^+\pi^+\pi^-$ events proceed through either the $N^{*++}\rho^0$ or $p\pi^+\rho^0$ intermediate states. They found that the $\pi^+\rho^0$ effective-mass distribution, $M(\pi^+\rho^0)$, for the $p\pi^+\rho^0$ events contains a broad enhancement (A^+) in the interval 1.0 to 1.4 BeV. Subsequent analyses by other groups showed that the enhancement consists of two peaks[2,3]: the A_1(1080) with $\Gamma = 80$ to 140 MeV and the A_2(1320) with $\Gamma = 80$ to 100 MeV. In their study of π^-p interactions Chung et al.[3] also observed peaks in the K_1K and $K_1\overline{K}_1$ systems at $M(K\overline{K}) \simeq 1310$ MeV with $\Gamma \simeq 80$ MeV; should the $\pi\rho$ and $K\overline{K}$ peaks represent alternative decays of the same initial state, it is likely that $I^GJ^P = 1^-2^+$ for the A_2. In contrast, the structure of the A_1 peak remains obscure. No related decays have been established; in addition, several kinematic origins for the enhancement have been suggested.[4-6] In the present Letter, properties of the $\pi^-\rho^-$ and $\pi^-\rho^0$ systems are compared under similar kinematic conditions. We conclude that the enhancements observed in the A_1 region cannot result from decay of an $I = 2$ state; our data in the A_2 region are consistent with decay of an $I = 1$ state produced through exchange of an $I = 1$ system. Interpretation of the A_1 enhancement as a kinematic effect is discussed.

To compare production and decay properties of the A_1 and A_2 systems in a variety of final states, we have analyzed π^-d interactions at 3.2 BeV/c. Thus far, the final states

$$\pi^- + d \to (p)n + \pi^- + \pi^- + \pi^+ \quad (2881 \text{ events}), \tag{1a}$$

$$\to (n)p + \pi^- + \pi^- + \pi^+ \quad (669 \text{ events}), \tag{1b}$$

and

$$\to (p)p + \pi^- + \pi^- + \pi^0 \quad (1577 \text{ events}), \tag{1c}$$

have been studied. Direct comparison of correlations with those observed in $\pi^\pm p$ experiments is significant only for events representing interactions on a single nucleon; in the impulse approximation, such events may be identified by the presence of a low-momentum spectator nucleon. Consequently, all events with a proton too short for observation (i.e., only three visible prongs) were measured[7]; four-prong events were measured only when a clearly identified proton was present. After fitting, events were assigned to Eq. (1a), (1b), or (1c), when the nucleon in parentheses had laboratory momentum $p_L \leq 220$ MeV/c.[8] With these criteria, all events corresponding to (1a) and (1c) were observed. The detection efficiency for (1b) decreases rapidly for events involving protons with $p_L > 800$ MeV/c; since the A enhancements in $\pi^\pm p$ interactions occur predominantly at low-momentum transfer squared, $\Delta^2(p)$, this bias does not affect the present conclusions.

To distinguish the two $\pi\pi$ pairs, $\Delta^2(\pi\pi)$ was calculated for each; we designate the pair with lower (higher) Δ^2 by $\pi\pi_1(\pi\pi_2)$ and the associated $N\pi$ pair by $N\pi_2(N\pi_1)$. The combined $M(N\pi)$ and $M(\pi\pi)$ distributions for the two $N\pi$ and $\pi\pi$ pairings are shown by the dashed curves in Fig. 1. Distributions for the $N\pi_2$ and $\pi\pi_1$ pairs are shown separately in the solid curves. The $M(N\pi_2)$ distributions for events in which the $\pi\pi_1$ pair lies in the ρ interval (600 to 850 MeV) are represented by the shaded areas in Figs. 1(a), 1(c), and 1(e); the N^* peaks in these distributions correspond predominantly to the $N^*\rho$ final state. The $M(\pi\pi_1)$ distributions associated with $N\pi_2$ pairs outside the N^* interval (1120 to 1320 MeV) are shown in the shaded areas in Figs. 1(b), 1(d), and 1(f); events in the ρ intervals in these distributions together with those in the $\pi\pi_2$ combinations are used in the final analysis.

The structure in the $(p)n\pi^-\pi^-\pi^+$ final state is similar to that observed in the charge-symmetric state, $p\pi^+\pi^+\pi^-$.[1] The $\Delta^2(\pi\pi)$ selection in Figs. 1(a) and 1(b) provides a remarkably clean separation of the $N^{*-}\rho^0$ events. Some N^{*-} and ρ^0 production occurs in the $n\pi_1$ and $\pi\pi_2$ pairs; however, the scatter plot shows no additional enhancement in the overlapping $N^{*-}\rho^0$ bands for these pairs. Correlations in the $(n)p\pi^-\pi^+\pi^-$ events are similar to those reported for the analogous final state produced in π^-p interactions at 3.2 BeV/c.[3] The $N^{*0}\rho^0$ final state is observed; however, the inset in Fig. 1(c) indicates that N^{*++} is stronger. Most π^+'s associated with the N^{*++} interval

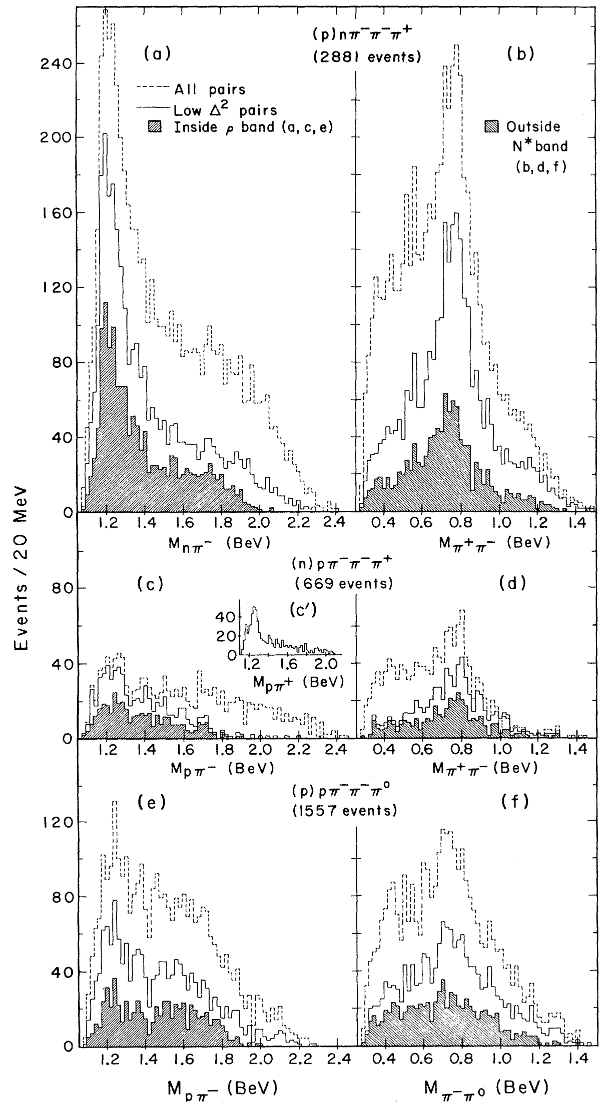

FIG. 1. Distributions of the invariant mass of $N\pi$ and $\pi\pi$ pairs. The dotted lines represent two combinations per event. The one combination per event for which $\Delta^2(\pi\pi)$ is the lower is represented by the solid lines.

combine with π_1^- to form ρ^0's; consequently, no unambiguous separation of $N^{*0}\rho^0$ events is possible. Some ρ^0 production occurs in both the $\pi\pi_1$ and $\pi\pi_2$ pairs outside the N^* interval. Structure observed in the $(p)p\pi^-\pi^-\pi^0$ final state consists predominantly of $N^{*0}\rho^-$ formation in the $p\pi_2^-$ and $\pi^0\pi_1^-$ pairs; negligible ρ^- production occurs outside the N^{*0} interval. Some uncorrelated N^{*0} and ρ^- formation is present in the $N\pi_1$ and $\pi\pi_2$ pairs.

To compare structure in the $\pi\rho$ systems produced in Reaction (1a), (1b), or (1c) a plot of $\Delta^2(\pi\rho)$ against $M^2(\pi\rho)$ is given in Fig. 2 for each final state. Events with either the $n\pi^-$ pair (1a), the $p\pi^+$ pair (1b), or either $p\pi^-$ pair (1c) in the N^* interval have been rejected. In Reactions (1a) and (1b) the $M^2(\pi^-\rho^0)$ distributions for events with $\Delta^2(\pi^-\rho^0) \leq 0.7$ (BeV/c)^2 show broad enhancements in the region 1.0 to 2.0 (BeV)^2; no separation of the A_1 and A_2 peaks is achieved. This is in qualitative agreement with the results of Goldhaber et al.[1]; however, with similar selection criteria, separate peaks were observed by Chung et al.[3,9] Almost all events whose assignment is ambiguous ($p_L \leq 220$ MeV/c for both nucleons) fall in the A_1 region; when the projections in Figs. 2(d) and 2(e) are added and ambiguous events used only once,[8] the relative intensities in the A_1 and A_2 regions tend towards those observed in the $\pi^{\pm}p$ experiments.

It is important to note that the strong $\pi^-\rho^0$ enhancements in the A_1 region are confined to events with $\Delta^2(\pi^-\rho^0) \leq 0.15$ (BeV/c)^2. In contrast, no analogous effect is observed when similar criteria are used to select $\pi^-\rho^-$ combinations[10]; within statistics, the $\pi^-\rho^-$ plot suggests a uniform density for $\Delta^2(\pi^-\rho^-) \leq 1$ (BeV/c)^2. Since the π^-d data reproduce the essential features of the corresponding $\pi^{\pm}p$ experiments, it is unlikely that this difference results from the presence of the additional nucleon in the final state.

Diagrams which may contribute significantly to $N\pi\pi\pi$ final states are shown in Fig. 3. In Fig. 3(a), exchange of a $G=-1$ system is allowed; when the exchanged particle is a pion [one-pion exchange (OPE)], this diagram contributes strongly to $N^*\rho$ events.[11] The presence of the pion propagator implies that with increasing c.m. energy, the OPE contribution tends to concentrate in the $N\pi_2$ and $\pi\pi_1$ pairs; this effect is particularly clear in the $(p)n\pi^-$-$\pi^-\pi^+$ final state. Recently, Deck has emphasized that the OPE diagram may also contribute significantly outside the N^* interval; in this case, the strong $\Delta^2(N)$ dependence for virtual πN scattering at vertex I in Fig. 3(a) results in a sharply peaked angular distribution in the πN c.m. system. This asymmetry is reflected as a low-mass $\pi\rho$ enhancement and provides a possible explanation for the A_1 peak.[5,12] In addition, this mechanism accounts naturally for the concentration of events in the A_1 region at $\Delta^2(\pi\rho) \leq 0.15$ (BeV/c)^2. For the $(p)p\pi^-\pi^-\pi^0$ final state, vertex I in Fig. 3(a) represents $\pi^0+n \rightarrow \pi^- + p$; consequently, it is possible that

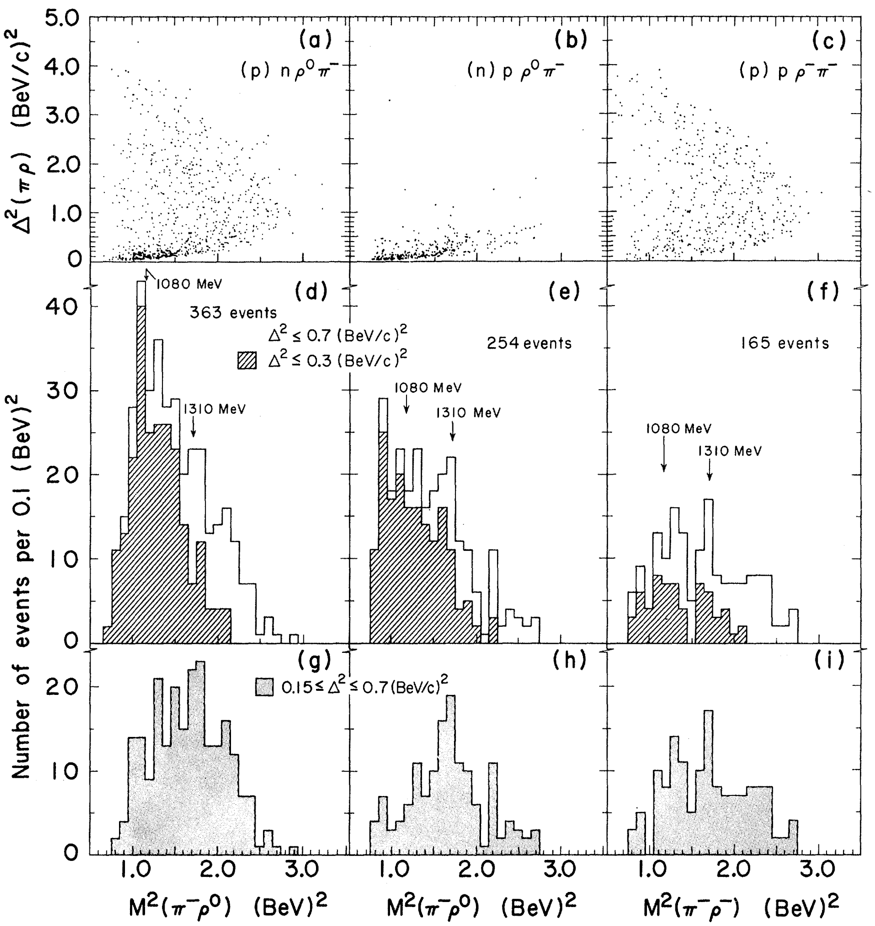

FIG. 2. (a), (b), and (c): Chew-Low plots of the $\pi\rho$ systems in Reactions (1a), (1b), and (1c), respectively. (d), (e), (f), (g), (h), and (i): projections of mass-squared ($\pi\rho$) for the same reactions. In all plots, events were excluded if neither $\pi^{+,0}\pi^-$ pair was in the ρ interval (600 to 850 MeV). Events with either $n\pi^-$ pair (a), the $p\pi^+$ pair (b), or either $p\pi^-$ pair (c) in the N^* interval (1120 to 1320 MeV) were excluded.

the absence of a significant $\pi^-\rho^-$ enhancement may be attributed to the small charge-exchange cross section above the N^* region.

In Fig. 3(b), the exchanged system must have $G=-1$; at low $\Delta^2(N)$, this diagram should dominate in the production of resonant states whose decay into 3π is strong. Assuming that the exchanged system is a ρ (since the dominant decay is $\pi\rho$), and neglecting absorptive effects, the relative rates for $A^- \to \pi^- + \rho^0$ [Reactions (1a) or (1b)] and $A^{--} \to \pi^- + \rho^-$ (1c) would be 1:1:0 for $I=1$ and 1:1:8 for $I=2$. To compare the experimental data in the A_2 region with these predictions, the low-mass $\pi\rho$ enhancements were suppressed[9] by using only the events with $0.15 < \Delta^2(\pi\rho) \leq 0.70$ (BeV/c)^2. To minimize statistical fluctuations, the distributions in Figs. 2(g) and 2(h) were combined; this yields a well-defined A_2^- peak of 50 ± 10 events centered at $M(\pi^-\rho^0) \simeq 1300$ MeV with $\Gamma \simeq 140$ MeV. If $I=2$ for the A_2, an enhancement of 200 ± 40 events should appear in Fig. 2(i). No evidence for any enhancement is observed; we conclude that the data are consistent with the assumption that the peak, $A_2^- \to \pi^- + \rho^0$, represents a system with $I=1$. A similar comparison for events with $\Delta^2(\pi\rho)$ less than either 0.15 or 0.30 (BeV/c)^2 indicates that the broad enhancements in the A_1 region observed in the present experiment cannot be attributed to decay of a state with $I=2$. We note also that the concentration of events in the A_1 region at $\Delta^2(\pi^-\rho^0) \leq 0.15$ (BeV/c)^2 would be unusual for production of any resonant state through ρ exchange. For example, in a study of the reaction $\pi^+ + n(p) \to \omega + p(p)$ at 3.25 BeV/c, Cohn, Bugg, and Condo[13] find significant ω production in the region $\Delta^2(\omega) \leq 0.6$ (BeV/c)^2. The $\Delta^2(\pi^-\rho^0)$ dis-

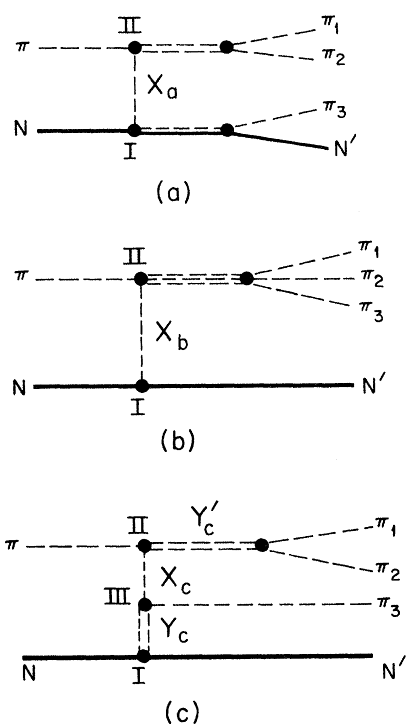

FIG. 3. Diagrams considered in the production of $\pi\rho$ enhancements.

tribution for A_2 events is similar to that observed in ω production.

Figure 3(c) represents a mechanism suggested by Nauenberg and Pais for generation of peaks in meson systems.[4] For real particles, π-Y_C scattering would show a peak in the mass region where the decay pion from Y_C could combine with the incident π to form Y_C'; they find that a 3π enhancement resulting from the sequence $\pi+\rho\rightarrow 3\pi\rightarrow\pi+\rho'$ should occur in the A_1 region.[14] If the mechanism were also effective for virtual $\pi\rho$ scattering, the relative A_1 peaks in Reactions (1a), (1b), and (1c) would be 1:1:2. Since no significant A^{--} peak occurs, this mechanism may be rejected.

An additional kinematic origin for the enhancement in the A_1 region has been suggested by Chang.[6] Since each final state contains two identical pions, symmetrization of the $N\pi\rho$ production amplitude may produce constructive interference at the 3π c.m. energy where either combination can form a ρ; subtraction of events with an $N\pi$ combination in the N^* interval emphasizes this region of interference. This effect is probably not important in Fig. 3(a) since Deck's calculation yields a strong low-mass $\pi\rho$ enhancement without symmetrization.[5] For Fig. 3(b), the effect can be distinguished from a genuine resonance only by demonstrating that the A_1 enhancement is not a pure state; this is not possible in the present experiment.

We conclude that the absence of any significant $\pi^-\rho^-$ enhancement precludes the interpretation of either A peak as the decay of an $I=2$ resonant state. Within statistics, relative production rates for the A^- enhancements in Reactions (1a) and (1b) are consistent with those expected for an $I=1$ state produced through ρ exchange.[15] When considered as a kinematic effect, several features of the data in the A_1 region are in qualitative agreement with predictions for the mechanism proposed by Deck.[5] The possibility remains that the A_1 peak in $\pi^{\pm}p$ experiments consists of a narrow resonance superimposed upon background enhancements from Fig. 3(a); observation of such a peak in the present experiment may be difficult because of decreased production on deuteron targets or because of poorer resolution.

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[1]G. Goldhaber, J. L. Brown, S. Goldhaber, J. A. Kadyk, B. C. Shen, and G. H. Trilling, Phys. Rev. Letters 12, 336 (1964).

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[3]S-U. Chung, O. I. Dahl, L. M. Hardy, R. I. Hess, G. R. Kalbfleisch, J. Kirz, D. H. Miller, and G. A. Smith, Phys. Rev. Letters 12, 621 (1964).

[4]M. Nauenberg and A. Pais, Phys. Rev. Letters 8, 82 (1962).

[5]R. T. Deck, Phys. Rev. Letters 13, 169 (1964).

[6]N. P. Chang, Phys. Rev. Letters 14, 806 (1965).

[7]Approximately 65% of the events measured had only three visible prongs; these correspond to a projected length of less than 1.5 mm for the low-momentum recoil. The fitting program treated the unseen proton as a measured track with momentum components equal to zero but having appropriate errors in the x, y, and z directions. For the four-constraint final state, $pp\pi^-\pi^-$, the resulting momentum distribution for the lower momentum proton is consistent with the Hulthén

distribution. With the weaker constraints in Reactions (1), the momentum distribution for unmeasured protons tends to peak at zero; the distribution for measured protons ($p_L > 80$ MeV) is consistent with the Hulthén distribution superimposed on a smooth background.

Since all three pion momenta are measured, mass resolution in the $\pi^-\pi^-\pi^+$ system, $\delta M \simeq \pm 20$ MeV, is not significantly affected by this distortion. An estimate for the mass resolution in the $\pi^-\pi^-\pi^0$ system, $\delta M \simeq \pm 30$ MeV, is obtained from the related fitting procedure used by W. J. Fickinger, T. C. Bacon, D. G. Hill, H. W. K. Hopkins, D. K. Robinson, and E. O. Salant, Bull. Am. Phys. Soc. 10, 587 (1965).

[8]Where the impulse approximation applies, more than 90% of the spectator nucleons have $p_L \leq 220$ MeV/c. In 167 events, $p_L \leq 220$ MeV/c for both the neutron and the proton; since the assignment of events is ambiguous in this case, alternative selections were tried. For the present analysis, 30 "double spectator" events are used in Fig. 2(d) only, 46 in Fig. 2(e) only, and 23 in both. The second selection, in which each event is assigned only to the final state corresponding to the lower momentum nucleon, leads to distributions which are not significantly different. An additional 700 events which contain no nucleon with $p_L \leq 220$ MeV/c have not been used.

[9]Although Chung et al.[3] observed separate A_1 and A_2 peaks for $\Delta^2(p) \leq 0.65$ (BeV/c)^2, they find that after deletion of events with $\Delta^2(p) \leq 0.15$ (BeV/c)^2 there is a strong emphasis of the A_2 peak with respect to the A_1.

Private communication.

[10]When events with $M(N\pi_2)$ in the N^* interval are not removed, all final states contain a strong $\pi\rho$ enhancement throughout the A_1 region at $\Delta^2(\pi\rho) \leq 0.15$ (BeV/c)^2.

[11]M. Abolins, R. L. Lander, W. A. Melhop, Ng.-h. Xuong, and P. M. Yager, Phys. Rev. Letters 11, 381 (1963).

[12]Alternatively, a genuine $\pi\rho$ enhancement at low mass erroneously attributed to Fig. 3(a) will simulate virtual πN scattering. Abolins et al., in Proceedings of the Second Topical Conference on Resonant Particles, Ohio University, Athens, Ohio, 10-12 June 1965 (to be published), have described a test for the mechanism proposed by Deck.[5] In the πN c.m. system, events in the N^* interval are divided into those in which the nucleon goes forward or backward with respect to the target-nucleon direction. They find that the low-mass $\pi\rho$ enhancement occurs only in the forward events. However, this correlation is simply a restatement of the fact that the A_1 enhancement occurs at low $\Delta^2(\pi\rho)$.

[13]H. O. Cohn, W. M. Bugg, and G. T. Condo, Phys. Letters 15, 344 (1965).

[14]In a more complete analysis, C. Geobel, Phys. Rev. Letters 13, 143 (1964), has shown that this mechanism is not likely to produce an enhancement by virtual ρ exchange.

[15]Similar conclusions have been reached by the La Jolla group in a study of π^-d interactions at 3.7 BeV/c (N. Xuong and R. Lander, private communication. See also reference 12.)

SEARCH FOR C-NONCONSERVING DECAYS $\varphi \to \rho+\gamma$ AND $\omega+\gamma$*

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In an attempt to explain the observed CP nonconservation in K_2^0 decay, a number of authors have suggested the existence of a C-nonconserving (but P-nonviolating) interaction.[1,2] Bernstein, Feinberg, and Lee (BFL) have noted that "all existing experimental results are compatible with the possibility of a very large violation of C and T invariance in the electromagnetic interaction of the strongly interacting particles."[3] C and T represent the usual charge-conjugation and time-reversal operators. BFL and others have considered possible C-nonconserving effects that would manifest themselves in the partial decay rates and resulting final-state asymmetries for the pseudoscalar and vector mesons.[4] Several experiments testing these predictions for pseudoscalar mesons are currently in progress, and the preliminary indication is that in at least one of these cases $[\eta(548) \to \pi^0+e^++e^-]$ the prediction is not fulfilled.[5]

Turning to the vector mesons, BFL show that if the Hamiltonian describing the electromagnetic interaction violates C, T invariance strongly, and if the isoscalar part of the C, T-nonconserving current exists, then the rate for $\varphi \to \omega+\gamma$ should be $\approx 1.9\%$ of the total φ-decay rate, and if the isovector current exists, the rate for $\varphi \to \rho+\gamma$ should be $\approx 2.4\%$ of the total φ-decay rate. Prentki and Veltman state that the rate $\varphi \to \pi^++\pi^-+\gamma$ (pions in S or P wave) may be as large as 10 to 20%.[6] Lee has further noted that in the limit of perfect SU(3) symmetry, one has $\Gamma(\varphi \to \omega+\gamma) \approx 0.79\,\Gamma(\varphi \to \rho+\gamma)$.[7] Owing mainly to phase-space limitations, the predicted branching ratio for $\omega \to \rho+\gamma$ is significantly suppressed below that for φ decay, and is undoubtedly consistent with the recent results of Flatté et al., giving $\Gamma(\omega \to \pi^++\pi^-+\gamma) < 0.05\,\Gamma(\omega \to \pi^++\pi^-+\pi^0)$.[8] The remain-