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Publication Date

1965-06-29

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Submitted to Physical Review Letters

UCRL-16237

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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James S. Lindsey and Gerald A. Smith

June 29, 1965

Search for C-Violating Decays $\phi \rightarrow \rho \gamma$ and $\omega \gamma$ *

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In an attempt to explain the observed CP violation in K_2^0 decay, a number of authors have suggested the existence of a C-violating (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-violating 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 [$\eta(548) \rightarrow \pi^0 e^+ e^-$] 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-violating current exists, then the rate for $\phi \rightarrow \omega \gamma$ should be $\approx 1.9\%$ of the total ϕ decay rate, and if the isovector current exists the rate for $\phi \rightarrow \rho \gamma$ should be $\approx 2.4\%$ of the total ϕ decay rate. Prentki and Veltman state that the rate $\phi \rightarrow \pi^+ \pi^- \gamma$ (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 $\Gamma(\phi \rightarrow \omega \gamma) \approx 0.79 \Gamma(\phi \rightarrow \rho \gamma)$.⁷ Owing mainly to phase-space limitations, the predicted branching ratio for $\omega \rightarrow \rho \gamma$ is significantly suppressed below that for ϕ decay, and is undoubtedly consistent with the recent results of Flatté et al. giving $\Gamma(\omega \rightarrow \pi^+ \pi^- \gamma) < 0.05 \Gamma(\omega \rightarrow \pi^+ \pi^- \pi^0)$.⁸ The remainder of this paper deals with our experimental observations on ϕ decay.

We have analyzed approximately 70% of 740,000 pictures taken of the 72-inch hydrogen bubble chamber exposed to an incident K^- beam at momenta of 2.1 to 2.7 BeV/c at the Bevatron. We consider the reactions

$$K^- p \rightarrow \Lambda^0 \phi^0 ; \phi^0 \rightarrow K^+ K^- , \quad (1)$$

$$K^- p \rightarrow \Lambda^0 \phi^0 ; \phi^0 \rightarrow K_1^0 K_2^0 , \quad (2)$$

and
$$K^- p \rightarrow \Lambda^0 \pi^+ \pi^- + (\text{all neutrals}) . \quad (3)$$

In Figs. 1 through 3 we present those events with the square of the momentum transfer to the Λ ($\Delta_{P,\Lambda}^2$) less than $0.8 (\text{BeV}/c)^2$. As observed in reactions (1) and (2), ϕ production is concentrated ($\approx 70\%$) in this momentum-transfer region.⁹

$\phi \rightarrow \rho \gamma$

Figure 1(a) is a scatter plot of the square of the (all neutrals) mass versus the square of the effective mass of the ($\pi^+ \pi^-$ all neutrals) combination from measured (unfitted) data for Reaction (3). The striking feature of this plot is the evidence for a π^0 at $M^2(\text{all neutrals}) = 0.018 \text{ BeV}^2$ for all values of $M^2(\pi^+ \pi^- \text{ all neutrals})$. However, for $M^2(\pi^+ \pi^- \text{ all neutrals}) \approx 0.92 \text{ BeV}^2$ one notices evidence for an enhancement at $M^2(\text{all neutrals}) \approx 0.0 \text{ BeV}^2$. This enhancement has been previously identified as the $\pi^+ \pi^- \gamma$ decay mode of the $\eta(959)$ (or X^0 meson).^{10, 11} In Fig. 1(b) we retain only those events in which the $\pi^+ \pi^-$ combination is in the ρ band (0.42 to 0.72 BeV^2). The

$\eta(959)$ enhancement remains, consistent with the results of Kalbfleisch et al. on the existence of the decay mode $\eta(959) \rightarrow \rho \gamma$.¹¹ No enhancement is observed at or near the known location of the ϕ , $M^2(\pi^+ \pi^- \text{ all neutrals}) = 1.038$ and $M^2(\text{all neutrals}) = 0.0 \text{ BeV}^2$. To demonstrate this more clearly the projections onto the $M^2(\pi^+ \pi^- \text{ all neutrals})$ scale are shown in Fig. 2. Only events in the range $-0.01 \leq M^2(\text{all neutrals}) \leq 0.01 \text{ BeV}^2$ are shown. The shaded area contains events in the ρ band only. The curves are a smooth approximation to the background. Using the $\eta(959)$ peak as a measure of our experimental resolution in this region, we find we can attribute no more than 20 events to $\phi \rightarrow \pi^+ \pi^- \gamma$ and 12 events to $\phi \rightarrow \rho \gamma$ with a confidence of 99%. Based on 209 examples of $\phi \rightarrow K^+ K^-$ and our measured branching ratio $\Gamma(\phi \rightarrow K^+ K^-) = (1.22 \pm 0.22) \Gamma(\phi \rightarrow K_1^0 K_2^0)$, we conclude that¹²

$$\Gamma(\phi \rightarrow \rho \gamma) \leq 0.03 \Gamma(\phi \rightarrow K\bar{K}) \text{ and } \Gamma(\phi \rightarrow \pi^+ \pi^- \gamma) \leq 0.05 \Gamma(\phi \rightarrow K\bar{K}). \quad (4)$$

$\phi \rightarrow \omega \gamma$

In as much as the neutrals of Reaction (3) contain both the π^0 from the ω decay and the photon, this all-neutrals combination has a wide variance of phase space for ϕ decay (0.048 to 0.55 BeV^2). Therefore, the scatter plot is not a particularly sensitive means of looking for this decay mode. In Fig. 3 we present the $M^2(\pi^+ \pi^- \text{ all neutrals})$ distribution, again at low momentum transfer. Events with $M^2(\text{all neutrals})$ less than 0.073 BeV^2 ($4m_{\pi^0}^2$) have been removed, since the $\Lambda^0 \pi^+ \pi^- \pi^0$ final state is such a large fraction of the background [see Fig. 1(a), for example]. Only events with a $\pi^+ \pi^-$ mass squared less than 0.420 BeV^2 , the upper limit for $\omega \rightarrow \pi^+ \pi^- \pi^0$ decay, are included. A large enhancement is observed at 959 MeV, due to the decay $\eta(959) \rightarrow \eta(548) \pi^+ \pi^-$, $\eta(548) \rightarrow \text{all neutrals}$, whereas no signal is observed

at 1019 MeV, the location of the ϕ . A further cut is made on the $\pi^+\pi^-$ mass squared less than 0.172 BeV^2 , the upper bound for $\eta(548) \rightarrow \pi^+\pi^-\pi^0$ decay. The remaining events are shaded [the $\eta(959)$ peak is further pronounced in reference to background by this selection because the $\pi^+\pi^-$ must have a mass squared less than 0.169 BeV^2 for this particular decay mode of the $\eta(959)$]. It should be noted at this point that if there existed a substantial C-violating strong decay $\phi \rightarrow \eta(548)\pi$ or a C-nonviolating electromagnetic decay $\phi \rightarrow \eta(548)\gamma$, these would show an enhancement at the ϕ mass, particularly in the shaded data. We find no evidence for these modes, and can attribute no more than 35 events to $\phi \rightarrow \omega\gamma$ and 25 events to $\phi \rightarrow \eta(548)\pi$ or $\eta(548)\gamma$ with a confidence of 99%. We thus conclude¹³

$$\Gamma(\phi \rightarrow \omega\gamma) \leq 0.09 \Gamma(\phi \rightarrow K\bar{K}) \text{ and } \Gamma(\phi \rightarrow \eta(548)\pi \text{ or } \eta(548)\gamma) \leq 0.15 \Gamma(\phi \rightarrow K\bar{K}). \quad (5)$$

Conclusions

Our results on the branching ratios for $\phi \rightarrow \rho\gamma$ and $\omega\gamma$ are compatible with the predictions of BFL. However, inasmuch as we establish only upper limits on these ratios it would be meaningless to compare them with Lee's prediction on the relative rates of these two modes. Our results on $\pi^+\pi^-\gamma$ (<5%) appear to be incompatible with the prediction of Prentki and Veltman (10 to 20%).

The authors acknowledge the skillful and dedicated support of Dr. Edward Lofgren and collaborators in the operation of the Bevatron, Mr. Robert Watt and collaborators in the operation of the bubble chamber, and all the scanning and measuring personnel who participated in this experiment. We thank Dr. J. J. Murray for his efforts with the beam and Professor Luis Alvarez for his continuing support.

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*Work done under the auspices of the U. S. Atomic Energy Commission.

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12. We must point out two minor qualifications to these results: (a) the cut on $|M^2(\text{all neutrals})| \leq 0.01$ results in the loss of a small fraction of $\eta(959)$ events due to resolution. Thus, we would expect this effect with approximately the same magnitude to occur in the case of the ϕ ; (b) our data at this time do not rule out the possibility of a weak alternate decay mode, $\phi \rightarrow \rho\pi$ (branching ratio = $18 \pm 8\%$). Again due to resolution we may be including a small amount of $\rho^0\pi^0$ in our $\rho^0\gamma$ and $\pi^+\pi^-\gamma$ determinations. The effect of (a) is to underestimate and (b) to overestimate the limits on $\rho\gamma$ and $\pi^+\pi^-\gamma$. However, the net effect can alter our conclusions on the branching ratios by no more than ± 1 to 2%.
13. We have assumed an all-neutrals branching ratio of 69% for the $\eta(548)$ and 10% for the ω in arriving at these branching ratios. We have introduced a slight bias in the $\omega\gamma$ and $\eta(548)\gamma$ determinations because of the removal of events with $M^2(\text{all neutrals}) < 4m_{\pi^0}^2$, inasmuch as the lower bound for these cases would be $m_{\pi^0}^2 [\omega \text{ or } \eta(548) \rightarrow \pi^+\pi^-\pi^0]$ or zero $[\eta(548) \rightarrow \pi^+\pi^-\gamma]$. Therefore, the branching ratios for these modes should be somewhat larger, but probably by no more than 1 to 2%.

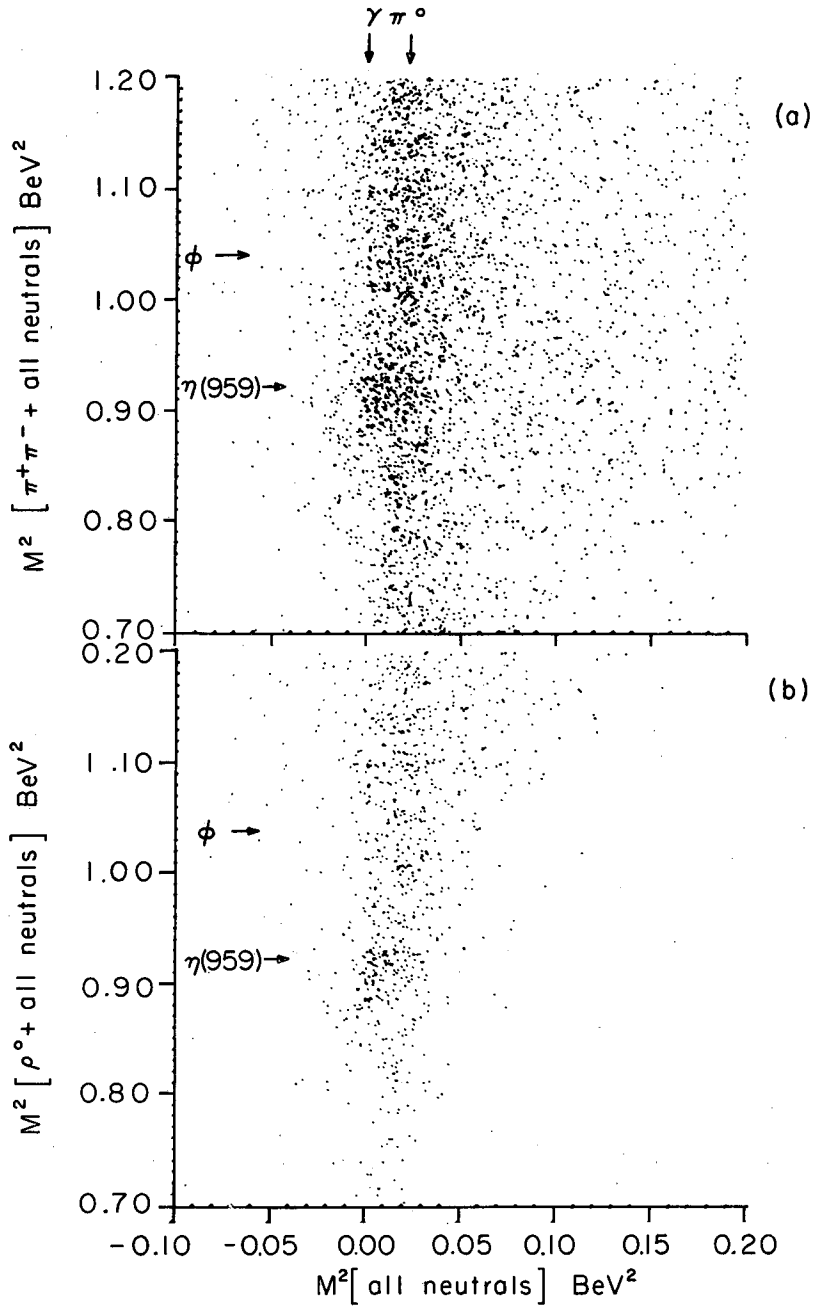
FIGURE LEGENDS

Fig. 1. (a) Scatter plot for 3468 examples of the reaction

$K^- p \rightarrow \Lambda^0 \pi^+ \pi^- + (\text{all neutrals})$ with the square of the momentum transfer to the Λ less than $0.8 (\text{BeV}/c)^2$, and (b) the same as (a), with the exception that only events with $M^2(\pi^+ \pi^-)$ in the range 0.42 to 0.72 BeV^2 (ρ band) are retained.

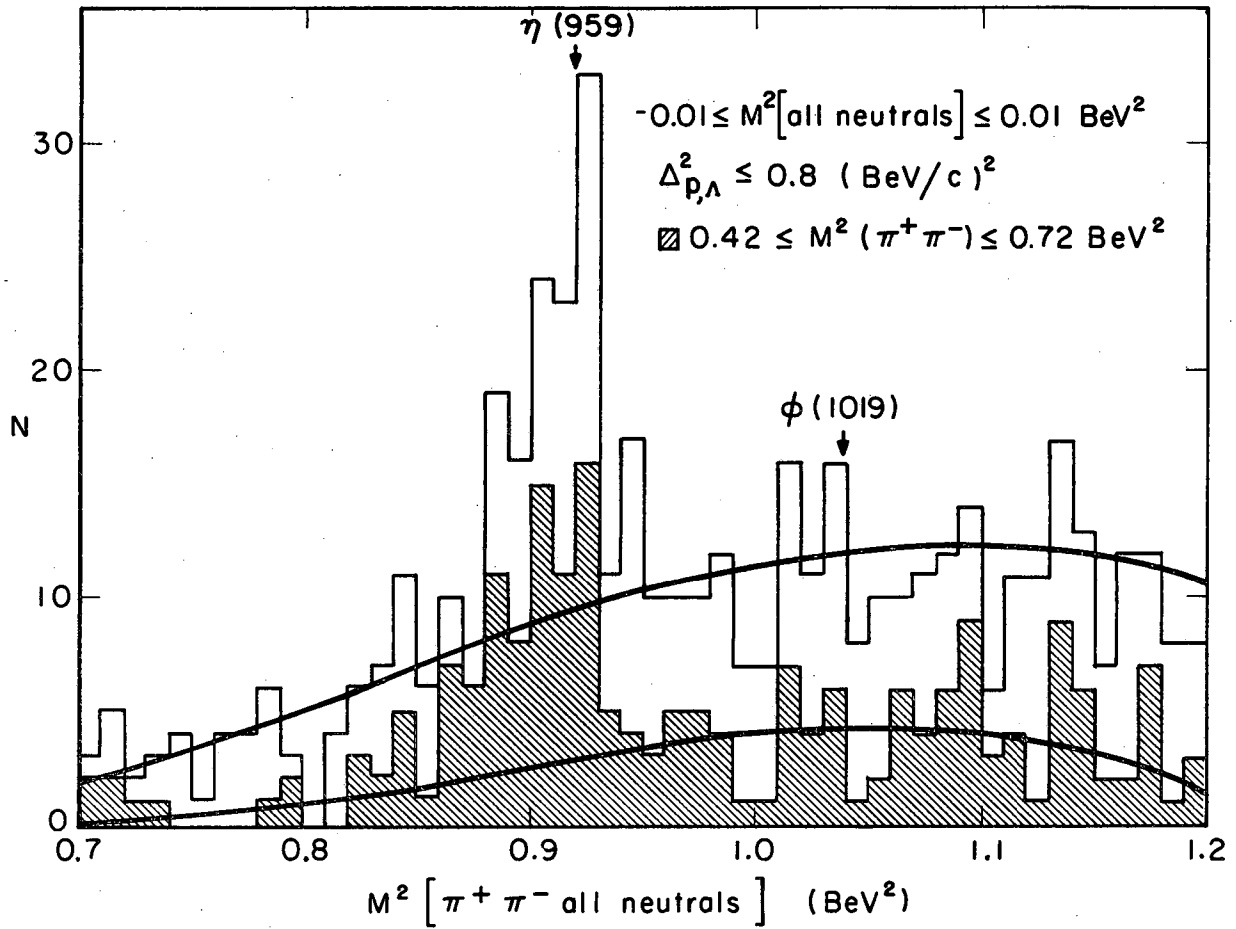
Fig. 2. Projection of the events of 1(a) in the interval $-0.01 \leq M^2(\text{all neutrals}) \leq 0.01 \text{ BeV}^2$ onto the $M^2(\pi^+ \pi^- \text{ all neutrals})$ scale. The shaded events are those plotted in 1(b) for the same intervals.

Fig. 3. Projection of the events of 1(a) in the intervals $M^2(\text{all neutrals}) \geq 0.073 \text{ BeV}^2$ ($4m_{\pi^0}^2$) and $M^2(\pi^+ \pi^-) \leq 0.420 \text{ BeV}^2$ (upper bound for ω decay). The shaded events have the further restriction $M^2(\pi^+ \pi^-) \leq 0.172 \text{ BeV}^2$ [upper bound for $\eta(548)$ decay].



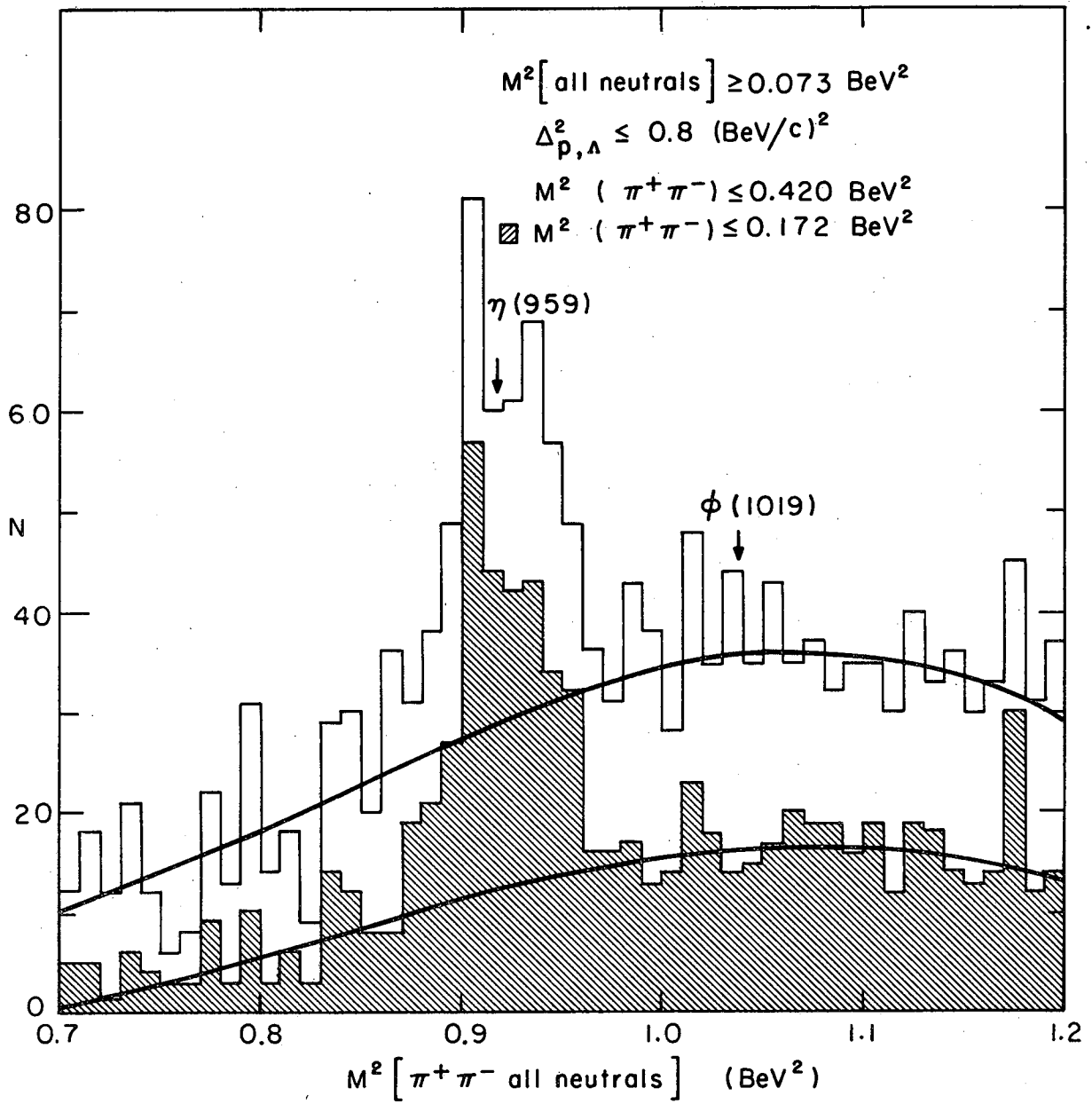
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Fig. 1



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Fig. 2



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Fig. 3

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