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SEARCH FOR C-VIOLATION IN η^0 MESON DECAYS*

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I. INTRODUCTION

As is well known since the time of the 1964 Dubna Conference, the long-lived component of the K^0 meson can decay through the following channels, in which the final pion states have CP-parity +1 and −1 respectively: $K_L^0 \to \pi^0 + \pi^0$ [1-3] and $K_L^0 \to \pi^+ + \pi^- + \pi^0$. All the attempts at explaining the presence of two such decay channels without CP-violation were disproved experimentally[4]. We must therefore agree that CP-invariance is violated at least in one of the terms of the Hamiltonian $H = H_S + H_\gamma + H_W + H'$ responsible for the K^0 decay. In addition, there are no essential reasons for us to reject CPT-invariance (see, for example,[5] †). As noted in[4], H' is a new interaction, many times weaker than the usual weak interaction H_W with $\Delta S \leq 1$ (for example, H' allows direct $K^0 \rightleftarrows \bar{K}^0$ transitions); however, certain predictions of such a scheme contradict the available experimental data[2,3]. As is well known, accurate to several percent[6], H_W does not violate T-invariance in decays with $\Delta S = 0$; the only experimentally observable CP-violation may occur in K^0-meson decays, where $\Delta S \neq 0$. The theory of weak interaction with CP-violation (the theoretical papers on this subject are listed in the report by Lee[7]) have no bearing on meson decay and will not be discussed.

Since the discovery of P-parity nonconservation in weak interactions, wide searches were made to verify P-invariance in nuclear physics. Experiments have shown that the P-violating amplitude is smaller than the P-even amplitude approximately by 10^5 times (for example, see[8]). Therefore only weak interactions can be regarded as P-violating, i.e., both strong (H_S) and electromagnetic (H_γ) interactions conserve P-parity. To explain the $K_L^0 \to 2\pi$ decays, two interesting theories were proposed. In the first, Prentki and Veltman[9] proposed that strong interaction H_S can violate C-invariance at the level of the SU_3-breaking coupling constants. Such a C-violation can become most strongly manifest in processes with large momentum transfers or in intermediate states including strange particles. Following the recent experiments with anti-proton-proton annihilation[10], we know that the upper limit for the ratio of the C-noninvariant to the C-invariant amplitudes in strong interactions is smaller than 10^{-2}. Bernstein, Feinberg, and Lee[11] advanced another interesting hypothesis: C-invariance can be strongly violated as a result of H_γ, inasmuch as a detailed study has indicated a complete absence of evidence favoring its holding in electromagnetic hadron interactions. In their theory, the electromagnetic hadron current J_μ^h is the sum of the classical current J_μ, which conserves C parity ($CJ_\mu C^{-1} = -J_\mu$), and a new current K_μ, which causes C-violation ($CK_\mu C^{-1} = +K_\mu$). The coupling constant in K_μ can be of the same order of magnitude as in J_μ. As follows from the subsequent exposition, the only place in which C-violation of H_S and H_γ would be readily observed is in η^0-meson decays. We know that at present there are no clear indications that C-violating effects have been observed in these decays.

In the present paper we present a review of some of the most characteristic experiments performed to verify C-invariance in η^0 decays, and compare their main characteristics, their distinguishing manifestations of C-violation, and their systematic errors. Finally, we shall show that it is exceedingly difficult to gain a deep understanding of the situation with η^0 decays at the present level of experimental technique.

II. POSSIBLE VERIFICATIONS OF THE THEORY WITH C-PARITY NONCONSERVATION

The present state of experiments in this field has already been discussed in the article by Finocchiaro; an exhaustive theoretical discussion of the question is contained, for example in[4]. It is shown in the cited papers that it is best to seek effects of C-violation in the decays of pseudoscalar mesons. The $\pi^0 \to e^+e^-$ decay with one photon in the intermediate state is P-forbidden; the probability of the $\pi^0 \to 3\gamma$ decay should be small compared with the probability of the $\pi^0 \to 2\gamma$ decay, owing to the additional smallness connected with the extra factor e, to the ratio of the phase volumes for 3γ and 2γ, and to the barrier factor due to the high orbital angular momenta. Thus, the most sensitive from the point of view of verifying the C-violating terms in H_S and H_γ are apparently the η^0- and η'-meson decays. The most exact of the presently available experimental results are the data on η^0 decays, since the η'-meson production cross section is small.

III. THEORETICAL PREDICTIONS ON THE η^0 MESON DECAY WITH C-PARITY NONCONSERVATION

The following C-violating η^0-meson decays are possible:

$$\eta^0 \to e^+ + e^- + \pi^0 \text{ *}), \quad (1)$$

$$\eta^0 \to \pi^+ + \pi^- + \pi^0, \quad (2)$$

$$\eta^0 \to \pi^+ + \pi^- + \gamma, \quad (3)$$

$$\eta^0 \to \pi^0 + \pi^0 + \gamma. \quad (4)$$

*Delivered at International Seminar on CP-violation Problems (Moscow, 22 – 26 January 1968).

†F. Stroccki (Phys. Rev. Lett. 19, 1456 (1967)) recently proposed an interesting model, in which CPT invariance is violated in the $K^0 \to 2\pi$ decay.

*Only in the case of an intermediate state with one photon.

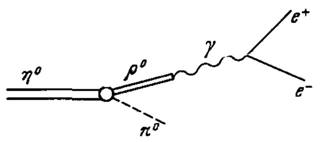

FIG. 1. Diagrm of $\eta^0 \to e^+e^-\pi^0$ decay with C-invariance violation in H_S.

Table I

Isotopic spin of the system $\pi^+\pi^-\pi^0$	Violation of C-invariance in the interaction: H_S	H_γ
0	$gx^3 \sin(\delta_0 - \delta_1)$	$e^2x^3 \sin(\delta_0 - \delta_1)$
2	$ge^2x \sin(\delta_2 - \delta_1)$	$e^2x \sin(\delta_2 - \delta_1)$

g – coupling constant of the C-violating strong interaction, equal to $\approx 10^{-2}$ according to experiments on pp annihilation), $x = m_\eta Q/M^2$, where Q – energy release, M – unknown mass, and δ_0, δ_1 and δ_2 – $\pi\pi$-scattering phases in states with I = 0, 1, and 2.

Table II

	With violation of C-invariance in the interaction: H_S (see [13])	H_γ (see [12])	In C-allowed transition (see [12])
$\frac{\Gamma(\eta^0 \to \pi^0 e^+e^-)}{\Gamma(\eta^0 \to \gamma\gamma)}$	$\cong 0{,}2\left(\frac{g_{\eta\rho\pi}}{4\pi}\right)^2$	$\alpha^2\left(\frac{m_e}{m}\right)^2 \cong 3\cdot 10^{-3}$	$\leqslant 10^{-8}$

$g_{\eta\rho\pi}$ – unknown coupling constant of $\eta\rho\pi$ interaction with C-parity nonconservation (it follows from the experiments with the annihilation [10] that $g_{\eta\rho\pi} < 10^{-2}$).

Unfortunately, calculations that do not depend on the choice of the concrete model can yield only rough estimates of order of magnitude for the probabilities of these decays.

The processes (3) and (4) are sensitive only to C-violation in H_γ. More accurately, if K_μ is taken in the form of a sum of only the isoscalar and isovector terms (as is usually done in the case of J_μ),

$$K_\mu = K_\mu^{\Delta I=0} + K_\mu^{\Delta I=1},$$

then the indicated decays can proceed only when $K_\mu^{\Delta I = 0} \neq 0$.

The process (1) can occur with C-parity conservation via two intermediate photons; then, however, its probability is much lower, as shown in [12].

The process (1) with C-violation is possible only in the presence of the term $K_\mu^{\Delta I = 1}$. It is also obvious that this decay can be due to violation of C-invariance in H_S, for example, as the result of the diagram considered by Barrett et al.[13] (see Fig. 1).

The process (2) may turn out to be sensitive to violation of C-invariance in H_S or H_γ. In this decay, and also in the process $\eta^0 \to \pi^+\pi^-\gamma$, C-parity nonconservation can be established by observing the asymmetry between the two charged pions, which results from the interference between the C-violating and C-conserving decay amplitudes. Making use of the concept of centrifugal barrier, Prentki has shown that such an interference can be appreciable only for amplitudes with I = 1 and I = 2. However, as shown by Lee[14], if the $\pi^+\pi^-$ interaction in the final state is negligibly small, this asymmetry is forbidden by the CPT-invariance requirement even in the case of strong violation of C-invariance. Indeed, the amplitudes of the C-violating decays (2) and (3) are proportional to $\sin(\delta_2 - \delta_1)$, where the phases δ_2 and δ_1 corresponding to the states with I = 2 and I = 1 are utterly unknown at present.

Only the decays (1), (2), and (3) have been investigated experimentally recently. Tables I and II contain a summary of the theoretical predictions concerning the order of the magnitude of the C-odd effects in these processes.

Finally, any $\pi^+\pi^-$ asymmetry in the $\eta^0 \to \pi^+\pi^-\gamma$ decay can be the result of only interference between P and D waves of the $\pi^+\pi^-$ system, with C-parities respectively equal to C = −1 and C = +1. As follows from estimates by Barrett and Truong[15], this asymmetry has an order of magnitude 10^{-2}. We note that in the theories indicated above it is assumed that the electromagnetic current $J_\mu + K_\mu$ does not contain terms with $\Delta I > 1$. After these theories were advanced, experiments[16] confirmed the validity of the indicated assumption. Thus, it is not necessary to introduce in K_μ a term with $\Delta I > 1$.

IV. EXPERIMENTAL SEARCHES FOR C-FORBIDDEN η^0 DECAYS

As already mentioned, only the decays $\eta^0 \to \pi^0 e^+e^-$, $\eta^0 \to \pi^+\pi^-\pi^0$, and $\eta^0 \to \pi^+\pi^-\gamma$ were investigated systematically. The first process was investigated with a high degree of accuracy in three experiments. The first and last of them used the method of heavy-liquid bubble chamber; in the second, an entirely different technique was used—a deuterium chamber with a tantalum plate, with the apparatus triggered with counters. The experimentally obtained upper limit for the partial width of the first decay, 10^{-3}, is apparently by now well established.

The situation in the other decays is not so clear. In order to obtain rapidly an estimate of C-violation in η^0 decays, all the available data on the $\eta^0 \to \pi^+\pi^-\pi^0$ decay in hydrogen chambers was summarized: as a result, a positive $\pi^+\pi^-$ asymmetry was obtained[14]. Already after the data obtained by entirely different methods have been unified, three experiments were performed, directly aimed at finding positive asymmetry, particular attention being paid to the systematic effects. The first such experiment, with a hydrogen chamber[18], gave positive asymmetry within the limit of two standard deviations. The second experiment[19], using exactly the same technique but half the statistics, revealed no essential asymmetry. Finally, an experiment with spark chambers[20], with very large statistics, likewise revealed no essential asymmetry. Thus, the situation calls for a very cautious analysis.

In conclusion we indicate that the experimental data on the $\eta^0 \to \pi^+\pi^-\gamma$ decay agree with each other and give no essential asymmetry, but the published results on the measurement of the partial width of the decay are not so good as in the case of the $\eta^0 \to \pi^+\pi^-\pi^0$ process.

1. The $\eta^0 \to \pi^0 e^+e^-$ Decay

As follows from Table II, the existence of this decay would be proof of C-parity nonconservation. The main experimental difficulty lies in verifying that the observed charged particles are electrons; this is precisely the fact that led to the registration, in the first of the experiments with the hydrogen chamber[21], of several unclear events, which could be interpreted either as $e^+e^-\pi^0$ or as $\pi^+\pi^-\pi^0$. To eliminate this ambiguity it is necessary to identify the secondary electrons by their bremsstrahlung loss. More accurate experiments, performed later, made use of heavy-liquid bubble chambers or a deuterium chamber with a tantalum plate.

a) Experiment of the Ecole Polytechnique-Berkeley collaboration[22]. The η^0 mesons were obtained from the reaction $\pi^-p \to \eta^0 n$ in a 300-liter heavy-liquid bubble chamber, exposed in a π^- meson beam with momentum 950 MeV/c from the "Saturn" proton synchrotron of Saclay. The photograph frames contained 750 $\eta^0 \to \pi^+\pi^-\pi^0$ events with subsequent decay $\pi^0 \to 2\gamma$, and both photons were detected. Figure 2a shows the distribution with respect to the invariant mass of the 2γ system for these events; the π^0-meson maximum is clearly pronounced, and the experimental resolution is $\approx 18\%$. Figure 3 shows the distribution with respect to the square of the invariant mass of the $\pi^+\pi^-\pi^0$ system; the experimental error in the magnitude of the three-pion mass is $\approx 8\%$, and the nonresonant $\pi^+\pi^-\pi^0$ background in the η^0-meson region is estimated at 10%.

In this experiment it is easy to detect the $\eta^0 \to \pi^0 e^+e^-$ decays by registering the characteristic deceleration of the two electrons as a result of the energy lost to bremsstrahlung (with efficiency $\approx 95\%$). On the other hand, the π^0 meson could be identified by the photons from its decay (at a 60% total-registration efficiency). The main background for this decay is due to the process $\pi^-p \to \pi^0\pi^0 n$, in which one of the π^0 mesons decays into γe^+e^-, and one of the photons produced as a result could not be registered. For 80 selected events that were possible candidates to be included among the $e^+e^-\gamma\gamma$ events, in Fig. 2b, no peak is observed in the distribution with respect to the invariant mass of the 2γ system; even a comparison with Fig. 2a indicates that the greater part of these possibilities are background events. No η^0 peak was observed in the distribution shown in Fig. 4, with respect to the invariant mass of the $e^+e^-\pi^0$ system for 40 $e^+e^-\gamma\gamma$ events having a 2γ-system mass compatible with the π^0-meson mass. Therefore all the registered $e^+e^-\gamma\gamma$ events can be regarded as a background. This background can be eliminated by introducing a suitable cutoff in the mass of the e^+e^- system, inasmuch as the distributions with respect to the invariant mass of the system e^+e^- for the decays $\pi^0 \to \gamma e^+e^-$ and $\eta^0 \to \gamma e^+e^-$ have high maxima at threshold values. A Monte Carlo calculation shows that only 15% of the actual number of decays $\eta^0 \to e^+e^-\pi^0$ in the exposed frames should have an invariant e^+e^--system mass lower than 100 MeV; however, in the selected events that could possibly be $e^+e^-\gamma\gamma$ events, the largest e^+e^- mass was 90 MeV. Thus, no $\eta^0 \to e^+e^-\pi^0$ events remain at all; after corrections are introduced for the cut-off (using the matrix element obtained in[11]) and for the registration efficiency, the following estimate is obtained for the upper limit of the decay probability, at a 90% confidence level:

$$\Gamma(\eta^0 \to \pi^0 e^+e^-)/\Gamma_{tot}(\eta^0) < 9\cdot 10^{-4}.$$

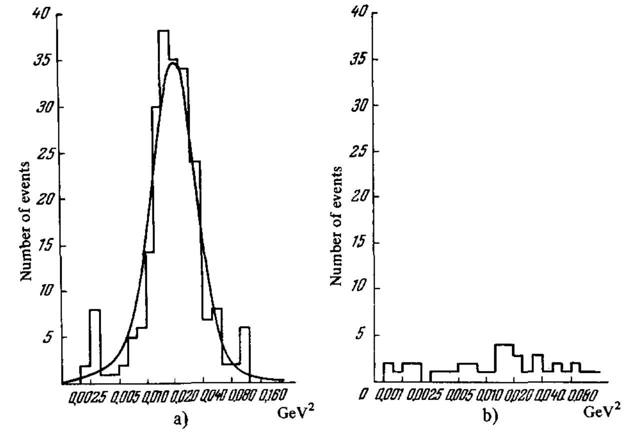

FIG. 2. Distribution with respect to the square of the mass of the 2γ system: a) for events $\pi^+\pi^-\gamma\gamma$ (the curve corresponds to a Monte Carlo calculation for the case $\pi^0 \to \gamma\gamma$); b) for $e^+e^-\gamma\gamma$ events.

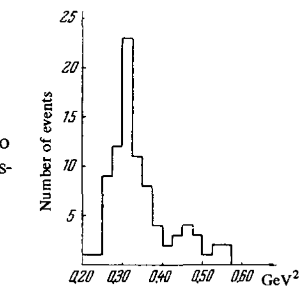

FIG. 3. Distribution with respect to the square of the mass of the $\pi^+\pi^-\pi^0$ system for $\pi^+\pi^-\gamma\gamma$ events corresponding to $\pi^0 \to \gamma\gamma$ decays.

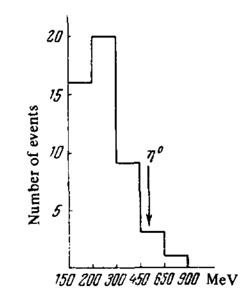

FIG. 4. Distribution with respect to the mass of the system $e^+e^-\pi^0$.

b) Experiment on the London-Oxford collaboration[23]. In this experiment the experimental technique was quite similar to that of the preceding experiment, and the equipment consisted of the heavy-liquid chamber of the University College (London) and the Rutherford Laboratory, exposed in a 930 MeV/c π^+-meson beam from the "Nimrod" proton synchrotron. The number of selected frames was double that of the preceding experiment. One $e^+e^-\gamma\gamma$ event was registered with an invariant e^+e^- mass equal to 240 ± 60 MeV, and with a 2γ-system mass compatible with the π^0-meson mass; however, the invariant mass of the entire $e^+e^-\gamma\gamma$ system was 410^{+20}_{-100} MeV. The positive error in the mass has been greatly reduced by the requirement of energy conservation in the η^0-meson production reaction. Consequently, one could be assured that this event is a possible error among the sought decays; the upper probability limit obtained in this case at a 90% confidence level is

$$\Gamma(\eta^0 \to \pi^0 e^+e^-)/\Gamma_{tot}(\eta^0) < 3{,}7\cdot 10^{-4}.$$

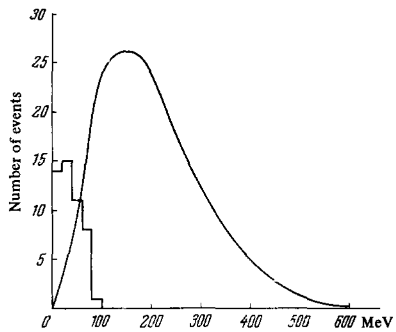

FIG. 5. Distribution with respect to the mass of the system e^+e^- for events $e^+e^-\pi^0$. The curve corresponds to a Monte Carlo calculation for the $\eta^0 \to e^+e^-\pi^0$ decay and takes into account the measurement errors (the theoretical spectrum is borrowed from [11]).

c) Experiment of the Princeton-Pennsylvania collaboration[24]. The η^0 mesons were obtained from the $\pi^+ d \to pp\eta^0$ reaction by 820 MeV/c π^+ mesons in the deuterium-filled bubble chamber with fast cycling, of the Princeton and Pennsylvania Universities. The experimental setup is shown in Fig. 6. The coincidence counters C_1 and C_2 separated the π^+-meson beam, and a tantalum plate two radiation units thick served to identify the secondary particles by their electromagnetic interactions. Behind the chamber was installed an absorber to retain the protons produced during the η^0-meson production process, as well as the electrons and photons produced during their decays. The triggering of the chamber and the actuation of the pulsed pushing magnet was by a coincidence signal from the counters C_1 and C_2 in the absence of a signal from the counters A.

During the scanning of the photographs, the e^+e^-pp events were detected by showers in the plate or by the ionization. After checking for coincidence with the initial η^0-meson production reaction, the number of possible cases of the sought decay was decreased to 12, of which certain events could be interpreted as $\eta^0 \to e^+e^-\gamma$ or $\eta^0 \to e^+e^-\pi^0$. The remaining five cases were identified as the decay $\eta^0 \to e^+e^-\gamma$, by detecting the emitted photon or by non-coincidence with a check for the presence of a π^0 meson. The experimentally obtained distribution with respect to the invariant mass of the e^+e^- system turned out to be compatible with the theoretical distribution for the $\eta^0 \to e^+e^-\gamma$ decay (Fig. 7). The total number of the produced η^0 mesons was found by normalization with respect to the process $\pi^+ + d \to p + p + \pi^0$ with subsequent decay $\pi^0 \to \gamma e^+e^-$.

Taking into account the efficiency of registration and triggering, and comparing by the maximum-likelihood method the distribution with respect to the e^+e^- system mass with the $\eta^0 \to \gamma e^+e^-$ hypothesis, we obtain with 90% confidence level the upper limit

$$\Gamma(\eta^0 \to \pi^0 e^+e^-)/\Gamma_{tot}(\eta^0) < 13 \cdot 10^{-4}.$$

d) Conclusions. The results of the described three experiments (in the last of which the procedure employed was quite unlike that in the first two) agreed with a value of less than 10^{-3} for the relative probability of the $\eta^0 \to \pi^0 e^+e^-$ decay.

If C-invariance is indeed violated in H_S, then it must be recognized that this result is not surprising, since the expected probability of the indicated η^0-meson decay is small (see Table II).

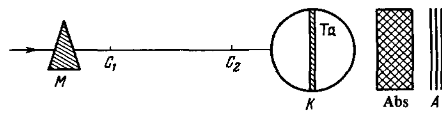

FIG. 6. Experimental setup. M – pulsed pushing magnet, K – chamber, Ta – tantalum plate, Abs – absorber.

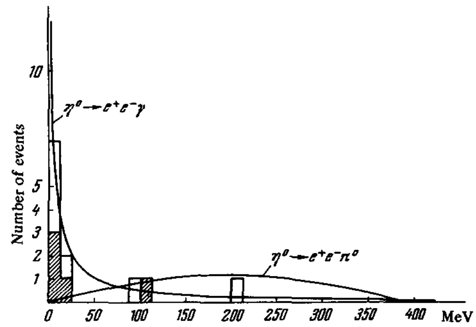

FIG. 7. Distribution with respect to the mass of the e^+e^- system. The curves correspond to the theoretical calculations; the shaded events are identified as cases of the $\eta^0 \to e^+e^-\gamma$ decay.

If the C-violation is connected with H_γ, then, as follows from Table II, this probability should be $\sim 2.7 \times 10^{-3}$, whereas the discussed experiments yield a result $< 3 \times 10^{-4}$ at a 90% confidence level. We can therefore conclude that if H_γ strongly violates C-invariance, then this violation is due apparently to the isoscalar term in K_μ, since the performed experiments exclude the possibility of a strong effect from the isovector term $K_\mu^{\Delta I = 0}$, and, as indicated above[16], there is no need to take into account any current with $\Delta I > 1$. Thus, it is necessary to verify the presence of an isoscalar term in K_μ by studying the asymmetry in the $\eta^0 \to \pi^+\pi^-\gamma$ decay.

Actually it is possible to reduce somewhat the theoretical value of the $\eta^0 \to \pi^0 e^+e^-$ decay probability, by assuming, as was done by Feinberg[25], that the C-invariance violating current K_μ is a member of an SU_3 octet. Then the $\eta^0 \to \pi^0 e^+e^-$ decay is allowed at the level of the SU_3-symmetry breaking interaction; the predicted partial width of the decay will then be one tenth as large as indicated in Table II, and will be comparable with the available experimental upper limit.

2. The $\eta^0 \to \pi^+\pi^-\pi^0$ Decay

We have already mentioned that as soon as the question of the possibility of registering C-violation in this decay was raised, an attempt was made[17] to unify the data of many hydrogen-chamber experiments. Thus, a positive value was obtained for the $\pi^+\pi^-$ asymmetry $R = (N_+ - N_-)(N_+ + N_-)$ for 1300 $\eta^0 \to \pi^+\pi^-\pi^0$ decay events. This was followed by an experiment by the Columbia University and State University of New York (Stony Brook) collaboration[18], aimed precisely at finding this possible asymmetry. After a thorough analysis of

Table III

Experiment		Process	Momentum GeV/c	N_η	ρ_b	ρ_π
№№	Group					
1	Columbia	$\bar{p}p \to \pi^+\pi^- + (\eta^0 \to \pi^+\pi^-\pi^0)$	0	149	0,52	—
2	»		2,5	47	0.36	0.08
3a	» Wisconsin-Purdue		1.225	134	0.02	0.16
3b	ditto		1.275	140	0.02	0.13
4a	Yale		1.225	78	0.03	0.14
4b	»	$\pi^+p \to p\pi_a^+ + (\eta^0 \to \pi_b^+\pi^-\pi^0)$	1.395	74	0.03	0.09
5	»		2,08	43	0.37	0,16
6	»		1.76	55	0.35	0,16
7a	Radiation Laboratory		1.05	41	0.02	0.10
7b	ditto		1,17	113	0.02	0,21
8a	» »		3,7	33	0,27	0,03
			Total:	758		
7c	» »	$\pi^-p \to p\pi_a^- + (\eta^0 \to \pi^+\pi_b^-\pi^0)$	1.17	60	0.02	0.20
8b	» »		3.7	9	0.50	0.11
			Total:	69		
9	» »	$K^-p \to \Lambda + (\eta^0 \to \pi^+\pi^-\pi^0)$	1.2 ÷ 1,8	309	0.31	0

N_η – approximate number of η^0 mesons in excess of background. $\rho_b = N_b/(N$ $(N_\eta + N_b)$ – fraction of background events in the η^0-meson mass region.

ρ_π – fraction of events, in the η^0-meson mass region, having a pion of unknown origin.

1441 $\eta^0 \to \pi^+\pi^-\pi^0$ decay events, a positive value was obtained for R, differing from zero within 2.5 standard deviations.

Somewhat later, exactly the same procedure was used by the Saclay-Rutherford Laboratory collaboration[19], in which no significant $\pi^+\pi^-$ asymmetry was observed for 705 $\eta^0 \to \pi^+\pi^-\pi^0$ decay events.

Finally, the CERN—Zurich—Saclay collaboration[20], using a spark-chamber method, observed no asymmetry at very high statistics—10,605 $\eta^0 \to \pi^+\pi^-\pi^0$ decays.

We shall now attempt to compare these different experiments to see what conclusion can be drawn from the agreement or disagreement between their results.

a) Result of the Columbia—Berkeley—Purdue—Wisconsin—Yale collaboration[17]. The difficulty of interpreting the result R = 0.058 ± 0.034, obtained by this group, lies in the fact that this result is a conglomerate of data obtained in a large number of completely different experiments. This can be illustrated by means of the following two remarks. First, the background of nonresonant events with $\pi^+\pi^-\pi^0$ in the η^0-meson region varied from experiment to experiment in the range 0.02—0.52 (Table III). Second, in some of these experiments, $\pi^\pm$ mesons were produced together with the η^0 meson, and this has led to events that cannot be uniquely interpreted, in which two π^+ (or π^-) mesons can, after combining with the remaining pair of particles $\pi^-\pi^0$ (or $\pi^+\pi^0$), yield the correct mass of the η^0 meson (Table III). In Table III are gathered some characteristics of the individual experiments used by the collaboration.

b) Experiment of the Columbia—Stony Brook collaboration[18]. In this group, the η^0 mesons were obtained in the $\pi^+d \to pp\eta^0$ reaction in the 30″ bubble chamber of the Columbia University and of the Brookhaven National Laboratory, placed in the 820 MeV/c π^+-meson beam of the Brookhaven alternating-gradient synchrotron. Searches were made here of interactions with four charged-particle prongs, two of which should be identified by ionization as protons, and the remaining as a possible $\pi^+\pi^-$ meson pair. Such events correspond to one of the following reactions:

$$\pi^+ + d \to \begin{cases} p + p + \pi^+ + \pi^-, & \text{(a)} \\ p + p + \pi^+ + \pi^+ + \pi^0, & \text{(b)} \\ p + p + \pi^+ + \pi^- + \gamma, & \text{(c)} \\ p + p + \pi^+ + \pi^- + n. & \text{(d)} \end{cases}$$

The chosen events corresponded, in accordance with the selection criteria, to the processes (a) and (b). The distribution with respect to the square of the missing mass and the distribution with respect to the effective mass of the $\pi^+\pi^-\pi^0$ system are shown for these cases in Figs. 8 and 9. The events were regarded to be identical with the $\eta^0 \to \pi^+\pi^-\pi^0$ decay if they corresponded, in accordance with the selection criteria, to the reaction (e) and did not correspond to the reaction (f) (see below), or else if they agreed with both reactions and had, in addition, a square of the missing mass larger than 0.007 (GeV)^2:

$$\pi^+ + d \to p + p + \eta^0, \quad \begin{cases} \eta^0 \to \pi^+\pi^-\pi^0, & \text{(e)} \\ \eta^0 \to \pi^+\pi^-\gamma. & \text{(f)} \end{cases}$$

The 1515 events selected in this manner contained also a certain background due to the nonresonant $\pi^+\pi^-\pi^0$ production. After cutting off part of the events with respect to the effective mass, a total 1441 events with a 7% background was finally separated. A Monte Carlo calculation has shown that the cases of true $\eta^0 \to \pi^+\pi^-\pi^0$ decays lost as a result of selection with respect to the total kinematics and other criteria cannot be the cause of the appearance of any asymmetry in the $\pi^{\pm}$-meson energies. A thorough verification of the possible sources of the asymmetry, other than C-violation, has led to an effect at a level of only 0.1%. As was emphasized in[26], this was preceded even earlier by an important control experiment using the decay $\omega^0 \to \pi^+\pi^-\pi^0$, to verify both *the operation of the chamber and the data-reduction* program. The asymmetry in the background events, at masses both lower than 520 MeV and higher than 580 MeV, was A = +0.08 ± 0.06. Taking into account the correction for this background effect, the asymmetry for the 1441 $\eta^0 \to \pi^+\pi^-\pi^0$ decays turned out to be

$$R = +0.072 \pm 0.028.$$

The distribution of these events on the Dalitz plane is shown in Fig. 10a.

On the basis of the presented asymmetry, which is reliable with accuracy up to 2.5 standard deviations and has the same sign as the result of the preceding summation of the individual experiments, the authors concluded that C-violation takes place in η^0 decays.

c) Experiment of the Saclay—Rutherford collaboration[19]. In this experiment they used precisely the same procedure as in the preceding experiment; these experiments differ only in the statistics. A total of 765 $\pi^+\pi^-\pi^0$ events was selected (see Fig. 10b). The background was estimated at 8% due to the nonresonant pions and 2.5% due to the $\eta^0 \to \pi^+\pi^-\gamma$ decay. The asymmetry of the background events was A = +0.10 ± 0.10. Taking into account this value, the asymmetry for the selected cases of the $\eta^0 \to \pi^+\pi^-\pi^0$ decay was equal to

$$R = -0.061 \pm 0.040.$$

Bearing in mind the resultant discrepancy between these two experiments, we can make the following three remarks:

1) The determination of the asymmetry of the background events A was quite poor in all these experiments.

2) Events with decay into $\pi^+\pi^-\pi^0$ were separated by a χ^2 cut-off in the effective mass squared from approximately 20 times more $\pi^+d \to pp\pi^+\pi^-$ events. Naturally, it was very difficult to determine the possible effect from the "tail" of the distribution of the indicated events.

3) Within the limits of two standard deviations, statistical fluctuations are not very unlikely.

d) Experiment of the CERN—Zurich—Saclay collaboration[20]. In this experiment, a spark chamber in a magnetic field was used. The η^0 mesons were obtained in the $\pi^-p \to \eta^0 n$ reaction with a 713 MeV/c π^--meson beam from the CERN proton synchrotron. The experimental setup is shown in Fig. 11. For the chamber to operate, the following requirements had to be satisfied: a) registration of the beam-particle interaction in the hydrogen target, b) passage of at least one charged particle through the counter F, c) detection of one particle by one of the neutron counters in a given time interval of 15 nsec duration. All these conditions correspond to the following coincidence signal from the counters: $S_1 S_2 \bar{A}_1 R F \bar{A}_2 \bar{A}_3 \bar{B} N_i$.

At a chosen π^--meson energy, the η^0-meson production cross section is quite large (~ 2 mb), and the $\pi^-p \to \pi^+\pi^-\pi^0 n$ (without η^0-meson production) proceeds near threshold. The neutron detectors were located at the

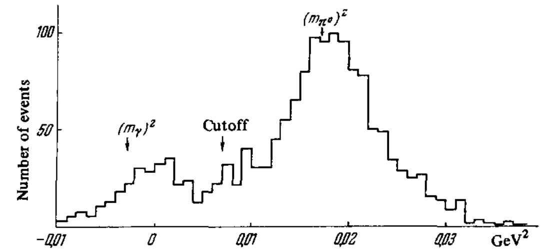

FIG. 8. Distribution with respect to the square of the missing mass of the X^0 system for the process $\pi^+d \to pp\pi^+\pi^-X^0$.

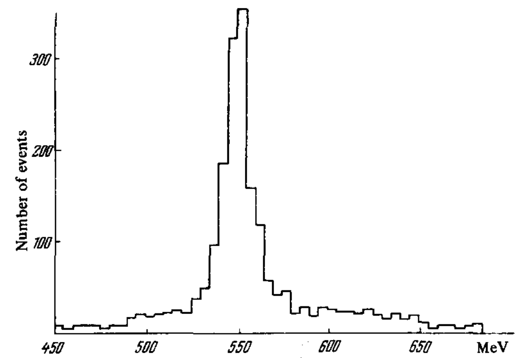

FIG. 9. Distribution with respect to the effective mass of the $\pi^+\pi^-\pi^0$ system in the process $\pi^+d \to pp\pi^+\pi^-$.

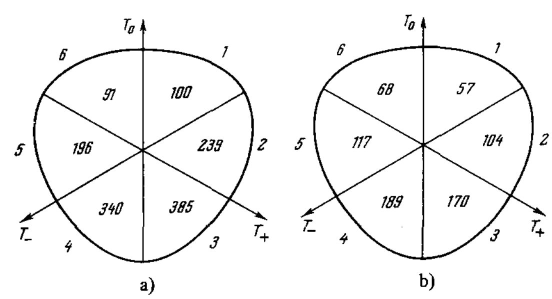

FIG. 10. Distribution of $\eta^0 \to \pi^+\pi^-\pi^0$ events on the Dalitz plane. a) Columbia – Stony Brook (R = +0.072 ± 0.028); b) Saclay - Rutherford (R = 0.06 ± 0.40).

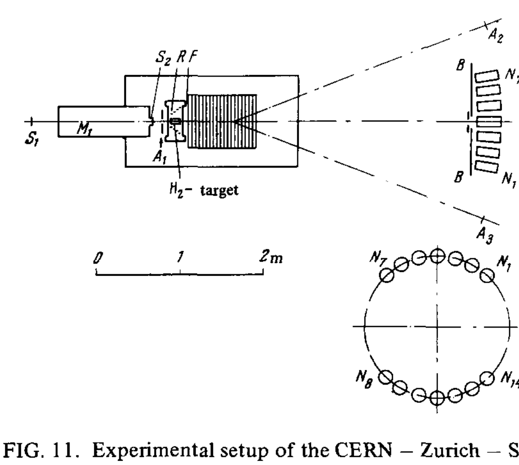

FIG. 11. Experimental setup of the CERN – Zurich – Saclay collaboration.

maximum lab-system angle permitted by the kinematics; then a very small angle interval (~ 2°) in this system spans approximately 50% of the total distribution in the c.m.s. Measurement of the neutron times-of-flight made it possible to select the neutrons having momentum values allowed by the kinematics (370–500 MeV/c), corresponding to a resolution ≈ 8 MeV in the effective-mass spectrum. During the scanning of the photographs, the only cases selected were those in which one neutron detector operated and there were two oppositely bent tracks passing through at least seven gaps of the spark chamber and having no kinks along this path. The experimentally obtained distribution with respect to the square of the missing mass relative to the $\pi^+\pi^-$-system mass is shown in Fig. 12; the maximum at the neutron mass value is due to the $\pi^-p \to \pi^+\pi^-n$ reaction. The corresponding events could be separated with the aid of a mass cut-off procedure. The peak at large values of the masses corresponds to the reactions

$$\pi^-p \to \eta^0 n, \quad \begin{cases} \eta^0 \to \pi^+\pi^-\pi^0, & (5) \\ \eta^0 \to \pi^+\pi^-\gamma, & (6) \end{cases}$$

$$\pi^-p \to \pi^+\pi^-\pi^0 n \text{ without } \eta^0\text{-meson production.} \quad (7)$$

Figure 13 shows the distribution with respect to the square of the masses of the neutral particles in the process $\pi^-p \to \pi^+\pi^-n$ + neutral particles. Measurements made with a π^--meson momentum reduced by 4% have made it possible to estimate that the background due to the reaction (7) amounts to 0.5 ± 0.2%; the asymmetry obtained in this case turned out to be A = 0.20. Those events which could be taken as $\eta^0 \to \pi^+\pi^-\pi^0$ decays were verified in accordance with the corresponding selection criteria, with two conditions superimposed. Each event was taken into account in the subsequent analysis with a definite weight, inversely proportional to the probability that the two pions do not interact in the hydrogen target (such a weighting procedure changed the asymmetry by only 0.2%). The distribution of the events weighted in this manner over the sextants of the Dalitz plot is shown in Fig. 14; the asymmetry corresponding to this distribution of all the 10,665 events of $\eta^0 \to \pi^+\pi^-\pi^0$ decays is 0.003 ± 0.010. To eliminate the effect connected with the asymmetry of the entire setup, the direction of the magnetic field was reversed every 12 hours of operation; thus, the entire experiment was symmetrical with respect to the vertical plane. The influence of such reversals of the magnetic-field direction on the incident beam, as shown by a Monte Carlo calculation, does not introduce an asymmetry in the energy distribution of the η^0-decay products. Nor was any appreciable asymmetry observed following long-hand reduction of those events which were described by the HPD automatic measuring device or by the THRESH three-dimensional track reconstruction program, but the corresponding statistical errors were taken into account in the final result. If the measured values are chosen for all the cases in lieu of the employed best values of the kinematic parameters, then the asymmetry turns out to be 0.007.

After introducing all the corrections, the following values are obtained for the total asymmetry:

$$R = 0{,}003 \pm 0{,}011.$$

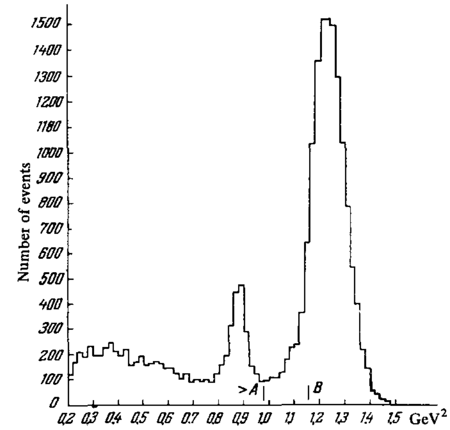

FIG. 12. Distribution with respect to the square of the missing mass relative to the $\pi^+\pi^-$ system for 21,606 events of the $\pi^-p \to \pi^+\pi^-nX^0$ process.

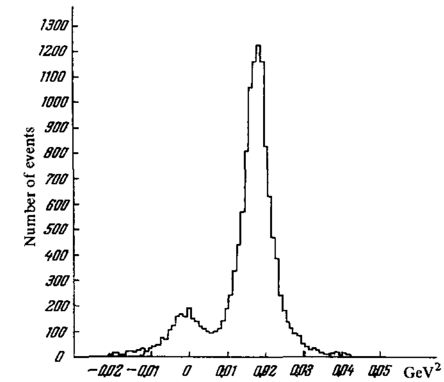

FIG. 13. Distribution with respect to the square of the mass of the X^0 system for 13,098 events of the $\pi^-p \to \pi^+\pi^- nX^0$ process.

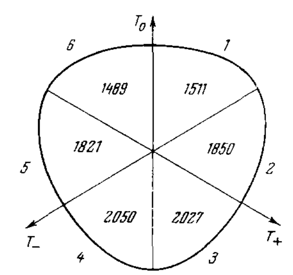

FIG. 14. Distribution of the $\eta^0 \to \pi^+\pi^-\pi^0$ decay events on the Dalitz plane.

The results of all the experiments on $\eta^0 \to \pi^+\pi^-\pi^0$ are summarized in Table IV, which is borrowed from Fitch's paper[26].

e) Conclusions. As noted by Fitch[26], the possible asymmetry can change on going from one region on the Dalitz plot to another. Therefore different weighting procedures or different filling of the Dalitz plane can lead to somewhat different results for the same experiment. Thus, in the case of the spark-chamber experiments, the registration efficiency can vary significantly over the Dalitz plane. Therefore, if the asymmetry actually exists and if it is particularly large in a certain part of the Dalitz plane, it is necessary to exercise caution in the comparison of data of different experiments.

Table IV

Experiment	Total number	By sextants						+	−	Asymmetry, %
		1	2	3	4	5	6			
Compilation	1300	119	199	361	298	205	101	679	604	5.8±3.4
Columbia-Stony Brook	1351	100	239	385	340	196	91	724	627	7.2±2.8
Duke	565	42	76	176	162	78	31	294	271	4.1±4.1
Rutherford - Saclay	705	54	126	151	174	139	61	331	374	−6±4
CERN - Zurich - Saclay	10665	1511	1850	2027	2050	1821	1489	5388	5360	0.3±1.0

At the present time we can merely state that there is no patent evidence favoring C-violation in the $\eta^0 \to \pi^+\pi^-\pi^0$ decay. As shown by Table I, this decay is most sensitive to C-parity nonconservation in a state with I = 2. However, even if C-invariance is violated only as a result of H_γ, a very small effect can be expected, in view of the presence of a centrifugal barrier and the interaction in the final state. Consequently, the real asymmetry in the $\eta^0 \to \pi^+\pi^-\pi^0$ decay, even if it does exist, should be of the same order of magnitude of the present experimental errors.

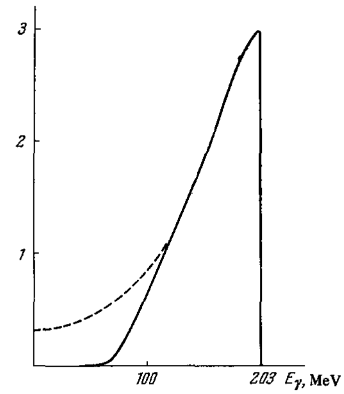

FIG. 15. Dependence of the registration efficiency (in relative units) on the photon energy E_γ.

3. The $\eta^0 \to \pi^+\pi^-\gamma$ Decay

So far, only two experimental results having a special bearing on C-parity nonconservation were obtained for this decay.

a) Experiment of the CERN—Zurich—Saclay collaboration[27]. The scheme of this experiment is the same as in that described above[20]. A total of 1620 $\eta^0 \to \pi^+\pi^-\gamma$ decays were registered, and the asymmetry turned out to be R = 0.015 ± 0.025.

This result calls for two remarks. First, a Monte Carlo calculation shows that the registration efficiency, just as in the $\eta^0 \to \pi^+\pi^-\pi^0$ decay, is a decreasing function of the invariant mass of the $\pi^+\pi^-$ system. Therefore the most appreciable effect is in the region of soft photons in the rest system of the η^0 meson (see the dashed line on Fig. 15). Second, as already noted, to separate from the background of the $\pi^-p \to \pi^+\pi^-n$ reaction, it is necessary to cut off the distribution with respect to the missing mass relative to the $\pi^+\pi^-$ system, and this leads also to discarding of $\eta^0 \to \pi^+\pi^-\gamma$ decay events with soft photons (see the solid curve on Fig. 15). Therefore, if any $\pi^+\pi^-$ asymmetry exists, corresponding to the soft-photon region, it would be difficult to observe in this experiment.

b) Experiment of the Rutherford—Saclay collaboration[28]. The experiment cited above[19] has made it possible to separate, out of all the η^0-meson production cases, 160 $\eta^0 \to \pi^+\pi^-\gamma$ events. The distribution with respect to the square of the effective mass of the $\pi^+\pi^-\gamma$ system, obtained for these events, is shown in Fig. 16. According to the estimates, the number of background events under the η^0 maximum was 22 ± 10. After correcting for the asymmetry of this background, the following result was obtained:

$$R = -0.02 + 0.08.$$

c) Conclusions. The two preceding results agree with the absence of C-parity nonconservation in $\eta^0 \to \pi^+\pi^-\gamma$ decays due to electromagnetic interactions. As indicated above, this decay is sensitive only to the isoscalar part of K_μ, if this part exists.

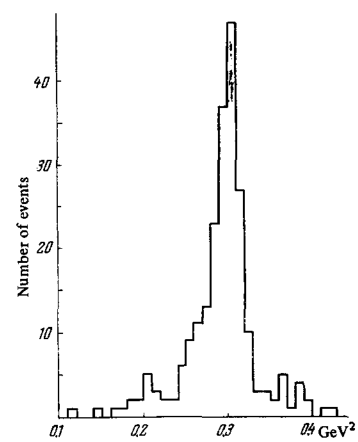

FIG. 16. Distribution with respect to the square of the mass of the $\pi^+\pi^-\gamma$ system.

Thus, we have no indication of the presence of C-noninvariant electromagnetic interaction in η^0 decays. However, as noted in[15], any violation of C-invariance in H_γ should produce an asymmetry on the order of 10^{-2} in the $\eta' \to \pi^+\pi^-\gamma$ decay. Therefore the experimental errors are patently too large to be able to draw any definite conclusion concerning this decay.

V. DEDUCTIONS FROM THE RESULTS OF ALL THE EXPERIMENTS

Summarizing, we arrive at the following general deductions.

1. There are no patent indications of C-invariance violation in η^0-meson decays.

2. The contemporary upper limit of the partial width of the $\eta^0 \to e^+e^-\pi^0$ decay denotes that the possible electromagnetic interaction that violates C-invariance strongly, if it exists at all, should be due principally to the term $K_\mu^{\Delta I=0}$ (we have seen that occurrence with $\Delta I > 1$ can be neglected); no account is taken here of the possible reduction of the indicated partial width, for example as a result of SU_3-symmetry requirements.

3. In the case of the $\eta^0 \to \pi^+\pi^-\pi^0$ decay, there exists one experiment with very large statistics, in which no asymmetry was observed at all. At the same time, the two presently available exact results of experiments with hydrogen chambers are contradictory; one of them, based on large statistics, leads to a positive value of the $\pi^+\pi^-$ asymmetry, corresponding to its maximum value predicted for this decay. It is thus clear that additional experimental information concerning this process is necessary.

4. At the present time, all the data are compatible with the presence of C-invariance, but its violation in η^0 decays is still possible: 1) at the level of semistrong interaction with a coupling constant smaller than 10^{-2}; 2) as a result of electromagnetic interaction with the pseudoscalar term $K_\mu^{\Delta I=0}$; 3) owing to the existence of a certain nonelectromagnetic interaction at the level of nonconservation of the isotopic spin.

VI. EXPERIMENTAL PROSPECTS

The presently available experimental data on η^0 decays can undoubtedly be improved, at least by increasing the statistics. To be assured of the absence of the $K_\mu^{\Delta I=1}$ term, it is necessary, in the case of the $\eta^0 \to e^+e^-\pi^0$ decay, to raise the upper limit for its probability to the level of the probability of the C-allowed decay. The presently existing upper limit, obtained in ordinary bubble-chamber experiments, cannot be improved by one order of magnitude without performing appreciable work. Real success can be achieved, for example, by the spark-chamber method, but in this method it is necessary to measure the characteristics of the electrons, something not performed in all cases so far.

The same remarks can be made with respect to measurements of the asymmetry in $\eta^0 \to \pi^+\pi^-\pi^0$ and $\eta^0 \to \pi^+\pi^-\gamma$ decays. To study these, a new experiments has now been set up*, using spark chambers and very large statistics, carried out by collaboration between Columbia University and the Brookhaven Laboratory. It should be borne in mind that the increase in the statistics in spark-chamber experiments should be accompanied also by equality of the registration efficiencies of events with different kinematics. This requirement is particularly important for the $\eta^0 \to \pi^+\pi^-\gamma$ decay; in this case, events with soft photons, when verified by the missing-mass criterion, are lost relatively frequently both in hydrogen and in spark-chamber experiments. Therefore the use of spark chambers under 4π-geometry conditions and with photon detection should lead to an appreciable progress.

Finally, direct searches for the C-violating decay $\eta^0 \to \pi^+\pi^-\gamma$ are much more difficult than earlier experiments, since the background due to the $\eta^0 \to \pi^0\pi^0\pi^0$ decay is very large (thus, e.g., serious difficulties arose[16] in the separation of the cases of the $\eta^0 \to \pi^0\pi^0\pi^0$ and $\eta^0 \to \pi^0\gamma\gamma$ decays).

Thus, without further appreciable work, experiments on η^0 decays can apparently not increase significantly our knowledge on C-invariance of hadron interactions. However, as already indicated, we can seek for parallel violation of C-invariance in η'-meson decays under better conditions. For example, the $\eta' \to \eta^0e^+e^-$ decay is not subject to strong limitations with respect to SU_3-symmetry. In turn, observation of the possible asymmetry in the decay $\eta' \to \pi^+\pi^-\gamma$, as shown in[15], may turn out to be much less limited as a result of the interaction in the final state than in the case of the $\eta^0 \to \pi^+\pi^-\gamma$ decay. Finally, present work being done on the development of large heavy-liquid chambers gives grounds for assuming that it will be possible to undertake searches of $\pi^+\pi^-$ asymmetry in the annihilation of antiprotons ($\bar{p}p \to \pi^+\pi^-\gamma$) with a registration efficiency 95%.

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