EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

POSSIBLE C, T VIOLATION IN ELECTROMAGNETIC INTERACTIONS

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INTRODUCTION

About three years ago Christenson, Cronin, Fitch and Turlay[1] discovered the existence of the decay $K^o_L \to \pi^+\pi^-$ (K^o_L being the long-lived component of the K^o, $\bar{K}^o$ system), with a branching ratio of about 2×10^{-3} with respect to $K^o_L \to$ all.

Up to that time the usual theories of this system incorporated CP invariance[*] and forbade absolutely this decay; the reason being that the $\pi^+\pi^-$ s-wave system is an eigenstate of CP, with eigenvalue +1. In fact, the absence of $K_L \to 2\pi$ decay was considered as the best evidence for CP conservation in all types of known interactions.

The most direct interpretation of the result[1] was to admit CP violation in weak interactions. However, since that time many other theoretical hypotheses have been advanced. Some of them are now ruled out by recent experiments.

Among the possible models one of the most fascinating ones connects CP violation with the electromagnetic interactions of the hadrons. The main part of these lectures concerns this model and its experimental tests (Sections 2 and 3).

The other models are treated in other lectures of the School and we simply mention them at the beginning, as well as their consistency with the data available at present (Section 1). The state of our knowledge about the validity of CPT and C, P, T invariances in the known interactions is also examined in Section 1.

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[*] K^o_S and K^o_L were described as eigenstates of CP, with eigenvalue +1 and -1 respectively (K^o_1 and K^o_2).

In Section 3 we describe in some detail the few existing experiments relevant to a possible C, T violation in electromagnetism, i.e. those on η decay.

1. $K_L^0 \rightarrow \pi\pi$ DECAY AND THE INVARIANCE PRINCIPLES: GENERAL REMARKS

1.1 An outline[*] of the attempts to explain the existence of the $K_L^0 \rightarrow \pi\pi$ decay

First of all, we want to remark that one interesting class of hypotheses, where CP is not violated "intrinsically" (i.e., by the interactions responsible for K^0 decay), has been ruled out by the experiments.

This is the case, for example, for a hypothetical "external" vector force, having its source in the galaxy, and coupled differently to K^0's and $\bar{K}^0$'s. Such a force would produce a partial "mixing" of K_1^0 and K_2^0, thus allowing $K_L^0 \rightarrow 2\pi$ decay. A detectable consequence should be a change of $K_L^0 \rightarrow \pi\pi$ decay rate with K_L^0 momentum. This is contradicted by experiments. Other models of the same "non-intrinsic" class are also contradicted by experiments[**], and those which are left are quite unpleasant, because they sacrifice basic principles like, for example, Bose statistics or the superposition principle.

It seems therefore reasonable to admit that CP conservation is not an absolute law of nature. One is then led to examine where and how an "intrinsic" CP violation may occur.

In the following we list the various classes of possible models and we indicate which of them are incompatible with recent experimental tests.

a) C and T are violated by a "semistrong" interaction H_V (conserving P and S), with a coupling constant smaller than the coupling constant of the strong interactions[3].

b) C, T violation occurs in H_γ, the electromagnetic interactions of hadrons[4]. The C-violating part still conserves P and S, and its coupling constant is of the same order as the electric charge.

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[*] For a complete review see the reports by J. Prentki at the 1965 Oxford Conference[2], and L.B. Okun and C. Rubbia at the 1967 Heidelberg Conference (to be published).

[**] Some of them predict the absence of interference phenomena between $K_S^0 \rightarrow 2\pi$, and $K_L^0 \rightarrow 2\pi$. On the contrary, interference has been observed.

c) CP violation appears at the level of weak interactions, with a coupling constant smaller than that of the CP conserving coupling, and with $\Delta S < 2$.

d) A $\Delta S = 2$, "superweak" interaction is responsible for CP violation.

In cases (a) and (b) one supposes that CP violation in weak interactions occurs through the interplay of the CP-conserving weak interaction (H_{wk}) and of the new C-violating interaction (H_V or H_γ), acting together.

The smallness of the observed effect in $K_L^0 \to 2\pi$ decay is attributed to the smallness of the CP non-invariant mixed term $H_V - H_{wk}$ (or $H_\gamma - H_{wk}$) with respect to H_{wk}, responsible for $K_S^0 \to 2\pi$ decay. In general, small effects are expected in most of the weak processes (there are however exceptions: see Sections 2.5 and 2.7).

On the other hand, particular enhancements of C-violating effects could a priori be expected in some processes - like η decay - where forces of the type invoked by models (a) and (b) could play an important role.

For class (a), we note that Prentki and Veltman$^{3)}$ proposed their model before some recent results on C violation in strong interactions (see $\bar{p}p$ annihilation in Section 1.2) had appeared. The new experiments do not exclude an explanation of $K_L^0 \to 2\pi$ decay with a semistrong interaction.

However, some properties which were tentatively assigned to H_V in the original proposal are now excluded. In particular, it is no longer possible$^{2)}$ to try to associate the hypothetical H_V with the SU_3 breaking interaction. Also, if one wants to assume a $\Delta I = 0$ $^{3)}$ selection rule for H_V, the magnitude of the predicted effects in a case like $\eta \to 3\pi$ decay is now too small$^{*)}$, compared with the present experimental sensitivities. In one sense, the situation becomes similar to the one of class (b) (isospin breaking could occur at this level).

The situation of model (b) is treated in Section 2.

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*) $\Delta I = 0$, C-violating transition amplitudes are strongly depressed in $\eta \to \pi^+\pi^-\pi^0$ decay by angular momentum barriers (see Section 2.4).

Various models of class (c) have been proposed. While there is still place for a possible explanation of $K_L^0 \to 2\pi$ decay, we only want to stress here that some of these models are now ruled out by recent experiments. This is the case in particular for models predicting a large μ polarization in $K_{\mu 3}$ decay transverse to the decay plane.

Two sensitive results are now available$^{5)}$, one for $K_L^0 \to \mu^+ + \pi^- + \nu$, the other for $K^+ \to \mu^+ + \pi^0 + \nu$, showing no effect.

Model (d) is now ruled out by the recently$^{6)}$ measured rate of the $K_L^0 \to 2\pi^0$ decay. In fact, one prediction of the "superweak" model, i.e.:

$$\Gamma(K_L^0 \to 2\pi^0)/\Gamma(K_L^0 \to \pi^+\pi^-) = \Gamma(K_S^0 \to 2\pi^0)/\Gamma(K_S^0 \to \pi^+\pi^-) \;^{*)} \qquad (1)$$

is incompatible with the new result.

Before treating model (b) extensively in Section 2, it is important to review the experimental situation of strong and electromagnetic interactions to see which are the present limits for possible violations of P, C, T invariances in each of these interactions (both of them determine the electromagnetic properties of hadrons).

On the other hand, as we are essentially interested in computing the magnitude of possible detectable effects within schemes of class (b), we shall assume in the following CP invariance of weak interactions.

1.2 Remarks on the present experimental limits on CPT and P, C, T invariances in the strong and electromagnetic interactions

Parity is known, since 1957, to be "maximally" violated in weak interactions. Since that time many experiments have been performed to search for possible P-violating effects in nuclear reactions. The P-non-conserving amplitudes come out to be smaller than the corresponding P-conserving amplitudes by, at least, a factor $\sim 10^{-5}$, which is about the order of magnitude of the dimensionless weak coupling constant $G_V \times m_p^2$ (m_p is the proton mass). Thus, it is consistent to regard both strong and electromagnetic interactions to be P-conserving (neglecting the weak coupling constant).

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*) $\Gamma(K_L^0 \to 2\pi^0)$ is here the decay rate $K_L^0 \to 2\pi^0$, etc.

The equality between the mass and the lifetime of any particle and of its antiparticle can be derived either by assuming CPT, or by assuming CP invariance of the interactions involved. Due to the fact that we are now examining the possibility of large CP and C violations, it is consistent to regard such equalities as evidence for CPT invariance.

A complete table of the present experimental data - updated to the time of the 1966 Berkeley Conference - is given in Table 1 (which is taken from the report by Fitch[5]). We note that, among the mass and lifetime equalities, the most accurate one is that concerning K^0 and $\bar{K}^0$:

$$\langle K^0 | H_{st} + H_{\gamma} + H_{wk} | K^0 \rangle = \langle \bar{K}^0 | H_{st} + H_{\gamma} + H_{wk} | \bar{K}^0 \rangle \qquad (2)$$

where H_{st}, H_{γ} and H_{wk} are respectively the Hamiltonians for the strong, the electromagnetic and the weak interactions. From the experimental mass difference Δm between K_1^0 and K_2^0, one can conclude that Eq. (2) holds to, at least, $\sim |\Delta M/m_K| \sim 10^{-14}$.

From the results on P and CPT invariances we can conclude, with great accuracy, that both H_{st} and H_{γ} are also invariant under CT.

The question is now to understand to which extent C and T hold separately in H_{st} and H_{γ}.

In strong interactions, there are various sources of evidence for C and T invariance. One of them comes from recent extensive studies of $p\bar{p}$ annihilation, both at rest[7]) and in flight[8]) at 1.2 GeV/c. The most significant result of the first experiment has a bearing on the annihilation into pions. In the second one, only annihilations involving kaons have been studied.

These results are quite important, due to the fact that one cannot use here models, based for example on SU_3 [2,9]), in which C-violating effects are depressed by the existing symmetries. Upper limits of about ~ 1-2% for a C-violating amplitude, both for those interactions involving pions and for those involving kaons, have been obtained.

The validity of T has been checked directly by testing the detailed balance principle in low energy nuclear reactions. An upper limit of about 2% has been obtained for the ratio of the T non-invariant to T-invariant amplitudes[10]. More precise experiments are going on[11].

Finally, the existing experiments on the polarization and angular asymmetry in the pp scattering give a corresponding limit of a few per cent[12].

The global analysis of the existing data on strong interactions excludes therefore any C, T violation at a level higher than a few per cent.

The problem of T and C invariances in the electromagnetic interactions is a quite complex one and will be treated in the next Section.

2. POSSIBLE C, T NON-INVARIANCE IN THE ELECTROMAGNETIC INTERACTIONS OF HADRONS

2.1 General hypotheses

The very precise experimental results on the anomalous magnetic moment of the muon[13] and on the Lamb shift, show that the electromagnetic interactions of both e and μ are accurately described by the usual form: $I_\mu \cdot A_\mu$, where

$$I_\mu = ie\,\psi^+ \gamma_4 \gamma_\mu \psi \tag{3}$$

is the lepton current*). This form is **explicitly** invariant under C, P and T.

For hadrons no such detailed theory exists, and if we do not assume a priori T and C invariance, the electromagnetic current operator I_μ has to be written in a much more general form than Eq. (3). In particular, from the point of view of its transformation properties under C one can write[4]:

$$I_\mu = J_\mu + K_\mu \tag{4}$$

where the part J_μ has the normal (odd)**) transformation properties:

$$C\,J_\mu\,C^{-1} = -J_\mu \tag{5}$$

and the (new) part K_μ, is even under C:

$$C\,K_\mu\,C^{-1} = +K_\mu \quad . \tag{6}$$

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*) ψ^+ and ψ are the lepton field operators. γ_μ, $\mu = 1, \ldots, 4$ are usual Dirac matrices.

**) Remember that $CA_\mu C^{-1} = -A_\mu$.

Both J_μ and K_μ are assumed to have the same transformation properties under CPT and both are vector currents (i.e. P is conserved: we have seen in Section 1.2 that this last feature is verified up to the order of the weak interactions).

Thus the condition of C or T invariance is

$$K_\mu = 0 \; . \tag{7}$$

If it now happens that $K_\mu \neq 0$ and if some of its matrix elements are comparable in magnitude to those of J_μ (i.e. large C, T violation), then virtual electromagnetic processes may induce C and T violation, to the order of α *), in all strong reactions.

Moreover, in the same spirit, the order of magnitude of the observed amplitude of the $K_L^o \to 2\pi$ decay may be roughly explained, by comparing it to the amplitude of the very similar process $K_S^o \to \pi^+\pi^-$.

In fact, the experimental ratio $\Gamma(K_L^o \to \pi^+\pi^-)/\Gamma(K_S^o \to \pi^+\pi^-)$ comes out to be of the order of $(\alpha/\pi)^2$, and it is tempting to associate CP violation in the $K_L^o \to \pi^+\pi^-$ decay with a supplementary virtual emission and absorption of a photon *) with respect to the process $K_S^o \to \pi^+\pi^-$.

Finally, quite large C, T-violating effects may a priori be expected in various processes where the role of the electromagnetic forces is dominant or important.

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*) In these, and other phenomena, where a real photon is not emitted, the C-violating amplitude must be proportional -- because of virtual emission and absorption of a photon -- to the coupling constant squared. Now, large C, T violation means that the coupling constant must be comparable in magnitude to the electric charge. Thus the corresponding amplitude should be roughly reduced by a factor α.

In the following paragraphs (Sections 2.2 to 2.8), we examine in some detail a series of processes of this type, to check whether the hypothesis of C, T violation in electromagnetic interactions is compatible with the present data, and where possible effects could be searched for.

2.2 Electromagnetic reactions involving baryons

We begin by listing some of the processes which could *a priori* be of interest:

- Elastic scattering of leptons on nucleons:

$$\ell^{\pm} + N \rightarrow \ell^{\pm} + N \qquad (8)$$

where $\ell = e$ or μ

- Electron (or muon) production of baryonic resonances $(N)^*$ 14)

$$\ell^{\pm} + N \rightarrow \ell^{\pm} + N^* \qquad (9)$$

- The decay5):

$$\Sigma^0 \rightarrow \Lambda^0 + e^+ + e^- . \qquad (10)$$

All of these phenomena can be described (to the lowest order in the electromagnetic interaction) through the Feynman diagram of Fig. 1, involving one photon exchange. Higher order contributions (involving more photons) can at most contribute interfering amplitudes smaller by a factor $\sim \alpha = 1/137$ and we shall neglect them in the following. Tests of T invariance in these reactions can in principle be performed through the search for correlation terms between the spin of one of the baryons and the momenta of the two leptons.

In the Compton effect on the proton15)

$$\gamma + p \rightarrow \gamma + p . \qquad (11)$$

T non-invariance may also give rise either to a polarization of the recoil proton, or to asymmetries in the angular distributions (when the reaction occurs on a polarized target). We shall not, however, treat this problem in more detail.

Other reactions in the list are:

- Direct and inverse photoproduction of the pion[16)]

$$\gamma + n \rightleftarrows \pi^- + p \qquad (12)$$

$$\gamma + p \rightleftarrows \pi^+ + n \qquad (13)$$

and also[16)]

$$\gamma + {}^3H \rightleftarrows \pi^- + {}^3He \qquad (14)$$

$$\gamma + {}^3He \rightleftarrows \pi^+ + {}^3H \qquad (15)$$

- Direct and inverse photodisintegration of the deuteron[17)]

$$\gamma + d \rightleftarrows n + p \; . \qquad (16)$$

In reactions (12) to (16), T invariance is checked through the validity of the reciprocity relations (comparison of the differential cross-sections for the direct and inverse processes at the same total electromagnetic energy).

The important question is now to understand which of all these reactions can really be sensitive tests of T [especially reaction (8), the most extensively studied one].

With this aim, let us examine the structure of vertex V_1, Fig. 1, or, more specifically, the general form of the matrix element of the electromagnetic current operator I_μ between two baryon states.

We consider, for simplicity, only the cases where the initial (N) and the final (N′) states both have spin $1/2$. The matrix element is*):

$$\langle N'|I_\mu(x)|N\rangle = ie\, u^+_{N'}\, \gamma_4[\gamma_\mu F_1 + i(N'_\mu + N_\mu) F_2 + i(N'_\mu - N_\mu) F_3]\, u_N \times \exp[-i(N'_\lambda - N_\lambda)\cdot x_\lambda] \, , \tag{17}$$

where N_μ and N'_μ are, respectively, the four-momenta of the initial and final single baryon states $|N\rangle$ and $|u'\rangle$, and $|u'\rangle$, u_N and $u_{N'}$ are the solutions of the free Dirac equations, and F_1, F_2, F_3 are functions of the square of the four-momentum transfer:

$$q^2 = (N'_\mu - N_\mu)^2 \tag{18}$$

only. The expression (17) is obtained by requiring invariance under the Lorentz transformation and space reflection*). From hermiticity*) of I_μ one finds that F_1, F_2 and F_3 must be all real. If one requires T invariance F_1 and F_2 must be real but F_3 must be purely imaginary*).

Thus

$$F_3 \neq 0 \tag{19}$$

implies T non-invariance. However, by imposing the conservation of current**), the T non-invariant term F_3 vanishes if the masses of the two baryons are equal (and they are on the mass shell).

The conclusion is therefore that no information on T invariance can be obtained by experiments on electron-proton scattering.

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*) Requirements coming from Lorentz invariance, hermiticity, and subsequently from C, P, T and CPT invariances are discussed, for example, in a report by Cabibbo and Veltman18).

**) Conservation of current can be written: $\partial\langle N'|I_\mu(x)|N\rangle/\partial x_\mu = 0$, using expression (17). Then the Dirac equation has to be used. The conventions about Dirac equation can also be found on page 69 in Ref. 18).

Some authors$^{4)}$ arrive at a similar conclusion also for the electromagnetic properties of the nuclei, to the extent that the approximation of regarding the nucleus as a collection of physical (on the mass shell) nucleons, is a good one. This approximation is estimated$^{4)}$ to be valid within a few per cent in the amplitude.

Thus, only to accuracies higher than this, can one hope to get information on C, T invariance of H_γ by the study of nuclear photoprocesses$^{*)}$. Details on this point are given in Section 2.8.

On the other hand, if the masses of the two baryon states N and N′ are different, the result obtained for the elastic scattering is no longer valid. One can hope to observe T-violating effects in reactions (9), (10), and also, in principle, (12) to (16), due to the role of virtual excited baryon states.

In the following, we examine in more detail some of these processes and some possible experiments. No data are available at present, except a few on reaction (10).

2.2.1 Electroproduction of resonances$^{14)}$. Here N′ represents any nucleon isobar (N*) or even a continuum of states. One should measure the correlation function $\underline{S}_{iN} \cdot \underline{P}_\ell \times \underline{P}_\ell'$$^{**)}$, where $\underline{S}_{iN}$ is the polarization of the target nucleon, and $\underline{P}_\ell$, $\underline{P}_\ell'$ are respectively the initial and final momenta of the lepton in the laboratory system. A useful quantity is the asymmetry parameter α, defined by:

$$\alpha = \frac{d\sigma(\uparrow) - d\sigma(\downarrow)}{d\sigma(\uparrow) + d\sigma(\downarrow)} ,$$

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*) Unless a contribution containing a large mass difference between two baryons happens to be emphasized by the presence of baryon resonances. See, for example, reaction (21).

**) It is important to note, that the existence of a correlation of this type is a proof of T violation only in the one-photon exchange approximation. In fact, it can also be generated by the interference term between the single-photon-exchange process and the two-photon-exchange process, without violating T invariance. However, the amount of such T-invariant correlation is small, since it contains an additional power of the fine structure constant α; furthermore, it is proportional to the sign of the charge of the lepton, whereas the T non-invariant term is not.

$d\sigma(\uparrow)$ and $d\sigma(\downarrow)$ being the differential cross-sections corresponding to initial polarizations $\underline{S}_{iN} = \hat{\underline{y}}$ and $\underline{S}_{iN} = -\hat{\underline{y}}$ respectively ($\hat{\underline{y}}$ is a unit vector parallel to $\underline{P}_\ell \times \underline{P}'_\ell$).

The case of electroproduction in the region of the $N^*_{3/2}(1236)$ has been studied in detail$^{19)}$ and, unfortunately, it seems not to be a favourable one, due to the relative values of the form factors involved. Thus, one should turn to higher masses, for example the $N^*_{1/2}(1518)$, which has already been observed in electroproduction$^{20)}$.

A typical experimental arrangement would require scattering on a polarized target, followed by momentum analysis of the secondary lepton.

The trouble is, however, that the present polarized targets provide a 60% polarization, but with only a 3% proton content; moreover the "background" nuclei are quite heavy. Thus the situation is quite difficult (unless one is able to produce new polarized targets, with higher H_2 content and lighter "background" nuclei).

2.2.2 $\underline{\Sigma^0 \to \Lambda^0 + e^+ + e^-}$. The matrix element $\langle \Lambda^0 | I_\mu | \Sigma^0 \rangle$ has also the general form (17). From current conservation one gets the following relation between form factors:

$$F_1 = (m_\Sigma + m_\Lambda)\ F_2 + (m_\Sigma - m_\Lambda)^{-1} \cdot q^2 \cdot F_3 \qquad (20)$$

with

$$q^2 = (\Sigma_\mu - \Lambda_\mu)^2 = M^2_{e^+e^-}$$

$M_{e^+e^-}$ being the effective mass of the e^+e^- system.

We are then left with only two independent form factors. One of them, related to F_1 and F_2, has to be proportional to q^2. Possible T-violating effects may arise from a difference of phase between the two independent form factors. One has to measure the polarization of the Λ^0 normal to the

Σ^0 decay plane. More specifically, if $\underset{=}{\sigma}_\Lambda$ is the Pauli spin matrix of the Λ^0, $\underset{=}{\hat{e}}^+$, $\underset{=}{\hat{e}}^-$, and $\underset{=}{\hat{P}}$ are unit vectors along the momenta of the e^+, the e^-, and the Λ^0 respectively, and if $\underset{=}{N} \equiv \underset{=}{\hat{P}} \times (\underset{=}{\hat{e}}^+ + \underset{=}{\hat{e}}^-)$ is the normal vector of the decay plane, then the (T-violating) quantity to be measured is $\langle \underset{=}{\sigma}_\Lambda \cdot \underset{=}{N} \rangle$.

The present experimental value is⁵⁾ 0.02 ± 0.02, obtained by using an unweighted average of 907 events. By weighting with polarization information the authors obtain 0.048 ± 0.026. There is however an inconsistency between the polarization and the pair mass distribution, indicating that one may be dealing with a statistical fluctuation.

New hydrogen bubble chamber experiments are now going on one order of magnitude better in statistics than the previous ones.

2.2.3 Test of reciprocity relations. Detailed calculations exist¹⁶⁾ for reactions (12) and (13). One of the troubles here is of an experimental nature: a neutron is always present as a target in one of the two reactions to be compared, and one has to use neutrons bound in deuterium. The limit on the precision is given here by our knowledge of deuterium.

Some theoretical calculations exist¹⁷⁾ also for reaction (16), where the experimental situation is better, due to the fact that deuterium itself (and not a bound neutron) is the target. A simple model and quite strong assumptions have been used. The basic idea is to attribute the possible failure of T invariance to the vertex $\gamma + N \rightleftarrows N^*$ appearing in the diagram in Fig. 2.

The searched-for effect should appear as a difference in the differential cross-sections of reactions (16) (direct and reverse processes), at the same total electromagnetic energy.

In this model a maximum effect of ~ 30% is estimated.

Due to the assumptions made, this value is probably quite optimistic, and one should use a much more sensitive apparatus to try to detect an effect.

Experimental data already exist on the direct reaction: $\gamma + d \to n + p$²¹⁾ at $P_\gamma \simeq 300$ MeV/c, corresponding to ~ 600 MeV kinetic energy of the neutron in the reverse reaction. On the other hand, a "monochromatic" neutron beam is now available at the CERN Synchro-cyclotron, so that the separation between the main $n + p \to \gamma + d$ reaction and the background reaction $n + p \to \pi^0 + d$ should become possible[22)].

Thus some interesting data could possibly come from this kind of experiment.

The conclusions of this Section can be summarized as follows:

In some processes, which could be of special experimental interest, the possible effects are forbidden or strongly depressed, independently of T invariance, just because of the form of the interaction involved (elastic scattering of electrons on nucleons and, partially, photonuclear reactions).

In the other cases, no data exist (excepting some poor results on Σ^0 decay) and there are in general big experimental difficulties to be overcome. Furthermore the predicted effects are in general quite small.

In the next section we shall see that the possible existence of isospin selection rules (connected with an isospin structure of K_μ) could introduce supplementary restrictions by suppressing some otherwise possible effects.

2.3 Remarks on the classification of T, C non-invariant interactions and on the definition of C

2.3.1 Isospin structure of K_μ. It is useful to put in evidence the isospin structure of both components of the current I_μ, by writing[4)]:

$$J_\mu = J_\mu^s + J_\mu^v \tag{21}$$

$$K_\mu = K_\mu^s + K_\mu^v \tag{22}$$

where the superscripts s and v indicate that these currents transform as an isoscalar ($I = 0$) or as an isovector ($I = 1$), respectively.

As is well known, evidence for the existence of both J_μ^s and J_μ^v is obtained, for example, in the form factors of the nucleons. On the other hand, if $K_\mu \neq 0$, some reactions are sensitive tests of either K_μ^s or K_μ^v only. Thus the distinction between the two terms of K_μ can be really important. In particular, if $K^V_\mu = 0$ (corresponding to a $\Delta I = 0$ isospin selection rule), many reactions which could be considered as direct proof of C non-invariance would be forbidden.

This is the case for $\Sigma^0 \to \Lambda^0 + e^+ + e^-$ decay and also for any electroproduction of resonances N* with $I \neq 1/2$. The same selection rule would also forbid many otherwise interesting meson decays*), etc.

The reverse is obviously true if $K^V_\mu \neq 0$ and $K^S_\mu = 0$ *).

2.3.2 Definition of C through the use of strong interactions. As we are investigating the possible C non-invariance of H_γ, it is no longer possible[4)] to use the electromagnetic interactions to define eigenstates and compute eigenvalues of C (for example, to use such decays as $\pi^0 \to 2\gamma$, $\eta^0 \to 2\gamma$, etc.). But we can still use the (C-invariant) strong interaction, if we assume that (strong) virtual transitions such as $N + \overline{N} \rightleftarrows \pi^0$ or $N + \overline{N} \rightleftarrows \pi^0$ can take place. In this case**):

$$C_{\pi^0} = +1 \;; \qquad C_{\eta^0} = +1 \;.$$

Also the definition of C for vector mesons (ω^0, ρ^0, Φ^0) is obvious because all of them decay into π or K systems, of definite C, via strong interactions.

We note that the present use of C consists of a change of a particle into its antiparticle, because it is under this operation that the strong interactions are known to be invariant. The use of this definition for lepton systems is not obvious, due to the absence of strong interactions. See a series of papers by Lee[23)] for this point.

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*) Several applications will be seen in the next sections.

**) As is well known: $C_{p\bar{p}} = (-1)^{\ell+s}$, where ℓ and s are respectively the orbital angular momentum and the total spin of the $p\bar{p}$ system.

2.4 Decays of the pseudoscalar mesons

The treatment of the electromagnetic interactions of the bosons is very similar to the one used for baryons. The same general principles are used to build up the matrix elements of the electromagnetic current I_μ.

The net result of the analysis of many decays -- which we anticipate now -- is that a large fraction of the a priori possible C-violating processes is forbidden or suppressed, independently of C invariance, because of the form of the interaction (as was the case for electron-proton elastic scattering).

Many other processes are strongly depressed simply by phase space, angular momentum barriers, or are just produced rarely and/or are difficult to detect.

So, the conclusion is that relatively few phenomena are possibly sensitive tests for C, T invariance. This is also true for the decay of vector mesons.

We now review the possible cases:

2.4.1 π^0 decay. In the one photon exchange approximation the mode $\pi^0 \rightarrow e^+ + e^-$ is forbidden because of parity conservation (higher order contributions being suppressed by a factor $\sim \alpha^2$, with respect to the "normal" $\pi^0 \rightarrow 2\gamma$ mode). If $K_\mu \neq 0$, the $\pi^0 \rightarrow 3\gamma$ mode is now allowed but its rate is strongly suppressed with respect to $\pi^0 \rightarrow 2\gamma$, by: (a) a factor α; (b) 3γ to 2γ phase space; and (c) centrifugal barrier effects. The computations are very much model-dependent. An estimate by some authors$^{4)}$ gives $\Gamma_{3\gamma}/\Gamma_{2\gamma} \sim 3 \times 10^{-6}$, but it could be much lower.

An experimental result by Soergel et al.$^{24)}$ gives an upper limit of 5×10^{-6} at 90% confidence level. A similar result also was obtained by Prokoskin et al.

Thus, the search for C-violating effects seems particularly difficult in π^0 decay.

2.4.2 η^0 and X^0 decays. Due to the small width of η^0 and X^0, these decays seem a priori to be among the most sensitive places to look for the effects of a possible C violating H_γ *). The following modes are of interest:

$$\eta^0 \to \pi^0 + e^+ + e^- \tag{23}$$

$$\eta^0 \to \pi^0 + \pi^+ + \pi^- \tag{24}$$

$$\eta^0 \to \gamma + \pi^+ + \pi^- \tag{25}$$

$$\eta^0 \to \pi^0 + \pi^0 + \gamma \tag{26}$$

$$X^0 \to \pi^0 + e^+ + e^- \tag{27}$$

$$X^0 \to \eta^0 + e^+ + e^- \tag{28}$$

$$X^0 \to \pi^+ + \pi^- + \gamma \tag{29}$$

$$X^0 \to \pi^0 + \pi^0 + \gamma \quad . \tag{30}$$

Reactions (23), (27) and (28) violate C, if they occur through a single photon exchange (higher order contributions would be depressed by $\sim \alpha^2$ in rate). Figure 3 shows the diagram corresponding to reaction (23).

Due to the absence of spins, only two form factors, f_1 and f_2, are involved and the general matrix element of I_μ for process (23) is:

$$\begin{aligned} \langle \pi^0 | I_\mu(x) | \eta^0 \rangle = {} & [f_1(\eta_\mu + \pi_\mu) + f_2(\eta_\mu - \pi_\mu)] \\ & \times [4\, m_\eta\, \omega_\pi]^{-1/2} \times \exp [i(\eta_\lambda - \pi_\lambda)\, x_\lambda] \end{aligned} \tag{31}$$

where η_μ and π_μ are, respectively, the four momenta of the initial η^0 and final π^0 states, m_{η^0} is the mass of η^0 and ω_π the energy of the pion. f_1 and f_2 depend only on $q^2 = (\eta_\lambda - \pi_\lambda)^2$.

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*) In both decays, and especially that of η, the electromagnetic forces play an essential role.

Conservation of current requires:

$$f_1 (m_\eta^2 - m_\pi^2) = q^2 \cdot f_2 \qquad (32)$$

so that if one assumes a slow dependence of f_2 on q^2, one can write[4)] f_1 in the form: $f_1 = -e/6 \langle \tau^2 \rangle \cdot q^2$ where $\langle \tau^2 \rangle$ is an average "charge distribution radius" squared.

Thus, with an assumption on the unknown value of $\langle \tau^2 \rangle$, one can compute the rate of process (23). If $\langle \tau^2 \rangle$ is arbitrarily set to be the mean square radius of the proton, then the ratio of the (computed) $\Gamma_{(\eta^0 \to \pi^0 e^+ e^-)}$ rate to the experimental[*)] $\Gamma_{(\eta^0 \to all)}$ rate is $R \simeq 3 \times 10^{-2}$ [the difference from the value quoted in Ref. 4) comes from the fact that $\Gamma_{\eta^0 \to all}$ was estimated there, whereas it has now been measured].

Experimentally, one gets[26)]:

$$\Gamma_{(\eta^0 \to \pi^0 e^+ e^-)} / \Gamma_{(\eta \to all)} < 0.3 \times 10^{-3} \qquad (33)$$

(at 90% confidence level). The discrepancy must be related to the assumption on $\langle \tau^2 \rangle$. Possible explanations are:

a) K_μ is a pure isoscalar: then $\langle \pi^0 | K_\mu | \eta^0 \rangle = 0$ and the transition is forbidden (Section 2.3).

b) K_μ transforms as the member of an SU_3 octet: in this case, and in the limit of exact SU_3 symmetry $\langle \pi^0 | K_\mu | \eta^0 \rangle = 0$; the matrix element is non-zero only due to contribution of the SU_3 - breaking interaction: an important depression is expected[27)].

More sophisticated calculations have been done by Feinberg[29)] assuming that the physical X and η are a mixture of a SU_3 singlet (X_1) and of the member (η_8) of the octet. The mixing angle is determined by using the Gell-Mann - Okubo mass formula: $\mathrm{tg}\, \Theta = 0.18$, and one can write:

[*)] $(\Gamma_{\eta^0 \to all}) = (2.7 \pm 0.7)$ keV [25)].

$$\eta = -X_1 \cdot \sin\Theta + \eta_8 \cdot \cos\Theta \qquad (34)$$

$$X = X_1 \cdot \cos\Theta + \eta_8 \cdot \sin\Theta\,. \qquad (35)$$

If $\langle \pi^0|K_\mu|\eta_8\rangle$ is assumed to be 0, the rate $\Gamma_{\eta\to\pi^0e^+e^-}$ is then depressed by a factor $\sin^2\Theta$ to a value ~ 2.4 eV.

The branching ratio $R' \simeq 10^{-3}$ computed in this way is not too far from the present experimental limit. The assumptions made are however quite strong *).

The model by Feinberg allows also a calculation of the rates of processes (27) and (28). The experimental data on the X^0 are however too poor.

2.4.3 $\eta \to \pi^+\pi^-\pi^0$ decay. Theoretical computations are model-dependent also in this case, due to the presence of three strongly interacting particles -- the pions -- in the final state. To start with, we limit ourselves to general arguments. More detailed arguments are given below.

Four values of the total isospin are possible a priori for a three-pion system -- i.e. I = 0, 1, 2, 3. States with total charge = 0 are eigenstates of C, with eigenvalues $C_{3\pi}$ univocally related to I, through $C_{3\pi} = G_{3\pi} \times (-1)^I$ (where $G_{3\pi} = -1$ is the 3π G parity).

So, transitions with $\Delta I = 0, 2$ do violate C invariance. Moreover, one can show that the symmetry properties of the 3π amplitudes with respect to the T^0 **), or y axis of the Dalitz plot (see Fig. 4) are simply related to

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*) It should also be stressed that the present knowledge of the X^0 is not very good (the evidence for a charged boson of the same mass and width, found by Maglić et al., makes the admitted set of quantum numbers doubtful).

**) We define a Cartesian coordinate system on the Dalitz plot with $x = (T^+ - T^-)/\sqrt{3}$ and $y = T^0 - Q/3$, where T^+, T^-, T^0 are respectively the c.m. kinetic energies of the π^+, π^- and π^0, and Q is the Q value of the decay. The point O(x = 0, y = 0) is the centre of the Dalitz plot, and its point of maximum symmetry (there $T^+ = T^- = T^0$), so that, due to the small range of variation of x and y over the plot, it seems reasonable to expand the various amplitudes in series of powers of x and y. This treatment is partially justified by the smoothness of the experimental distribution function of the points over the Dalitz plot (as a matter of fact the present evidence for quadratic terms in the expansion is at the limit of the experimental errors).

One can define also six sextants on the Dalitz plot, as the regions where the conditions $T^i > T^j > T^k$, are verified for each of the six possible permutations of the indices $i, j, k = \pi^+, \pi^-, \pi^0$.

to the I value of each state. Also, interference terms between amplitudes corresponding to opposite C eigenvalues change sign when passing from one region of the Dalitz plot to the symmetric one.

Thus, the contribution of the interference term gives rise to a difference of population between symmetric regions of the Dalitz plot. One can define a (measurable) asymmetry between such regions as

$$A = (N^+ - N^-)/(N^+ + N^-)\ ^{*)} \tag{36}$$

where N^+ is the number of events in which the energy of the π^+ is larger than that of the π^- (and inversely for N^-).

It should be noted that, as a consequence of CPT invariance, amplitudes corresponding to opposite C values are relatively imaginary[27) $[(\varphi_B - \varphi_C) = \pi/2)]$, if final-state interactions among pions are negligible. Interference terms vanish in this case and no effect can be observed, even if C violation occurs.

In order to estimate roughly the order of magnitude of the asymmetries related to the various possible transition amplitudes, one has to take into account the quenching effect of the centrifugal barriers on each amplitude. Such an effect can be represented roughly through powers of (KR), (K being the mean momentum of a pion, and R an unknown interaction range which one could assume to be of the order of the inverse of M_η, the η mass).

The power of KR appearing in each amplitude is related to the symmetry properties of the state (and its isospin).

No quenching occurs for the dominant $I = 1$ totally symmetric state[28). Factors $(KR)^6$ and $(KR)^2$ correspond respectively to $I = 0$ and $I = 2$[28). Thus, one expects a strong depression of possible effects related to a $\Delta I = 0$ transition amplitude.

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*) The asymmetry A is related to the interfering amplitudes B and C by

$$A = \frac{2\ \mathrm{Re}\ (B \cdot C^*)}{|B|^2 + |C|^2} \simeq 2\ \frac{|B|}{|C|} \cdot \cos\ (\varphi_B - \varphi_C) \tag{37}$$

(if $|B|^2 << |C|^2$). $(\varphi_B - \varphi_C)$ is the phase difference between B and C.

A reasonable order of magnitude could still be expected for an asymmetry A arising from interference of I = 1 and I = 2 states. In this case the global right-left asymmetry should be roughly[28]

$$A \sim 2(KR)^2 \sin(\delta_1 - \delta_2) \qquad (38)$$

where δ_1 and δ_2 are the (unknown) strong interaction 3π eigenphase shifts in the I = 1 and I = 2 states respectively. If one assumes $R = 1/M_\eta$, one can get asymmetries of the order of 5%*) [if $\sin(\delta_1 - \delta_2)$ is not small]. The point is, however, that no accurate calculation is possible; in particular, the value of R, and, more generally, the quenching effects can only be estimated qualitatively. It should also be emphasized that nothing is known at present about $\delta_1 - \delta_2$.

Several experimental results exist at present on $\eta \to \pi^+\pi^-\pi^0$ decay and will be reported in Section 3. In this section we only mention the most significant one, i.e. that of the CERN-ETH-Saclay group[29]

$$A = (0.3 \pm 1.1)\% \qquad (39)$$

showing no effect within the errors.

An analysis taking into account not only the global right-left asymmetry, but also more detailed features of the Dalitz plot can be done if one assumes that the possible effect is due either to a $\Delta I = 2$, or to a $\Delta I = 0$ transition only. If one takes only the lowest order terms in the expansion mentioned in the footnote to page 20, the asymmetry comes out to be proportional to $|x|$ (or $|T^+ - T^-|$), in the pure $\Delta I = 2$ hypothesis. On the other hand, in the pure $\Delta I = 0$ hypothesis, the asymmetry computed for pairs of symmetric sextants comes out to change of sign when passing from one pair to the neighbouring one**).

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*) The average π momentum is $K \simeq 150$ MeV/c.

**) More precisely the amplitude for the $\Delta I = 0$ transition (and thus the asymmetry) is proportional to the product $(T^+ - T^-)(T^- - T^0)(T^0 - T^+)$[30].

Figures 5 and 4 show the asymmetry as a function of $|T^+ - T^-|$ as well as the number of events per sextant in the CERN-ETH-Saclay experiment. No effect is visible.

As already mentioned, at the present level of experimental sensitivity, the $\eta \to \pi^+\pi^-\pi^0$ should be essentially a test of the presence of $\Delta I = 2$ transitions only (i.e. of K^V_μ only), $\Delta I = 0$ transitions being depressed by the centrifugal barriers.

Thus the results of the experiment by Cnops et al$^{29)}$ should be interpreted together with the result of Bowen et al.$^{31)}$ as an indication against the existence of K^V_μ. Due to the lack of knowledge of certain parameters, this interpretation is however not unambiguous.

Further details on the CERN-Zurich-Saclay experiment will be given in Section 3.

2.4.4 $\underline{\eta^0 \to \pi^+\pi^-\gamma \text{ decay}}$. The evaluation of possible effects in $\eta^0 \to \pi^+\pi^-\gamma$, $\eta^0 \to \pi^0\pi^0\gamma$, $X^0 \to \pi^+\pi^-\gamma$, $X^0 \to \pi^0\pi^0\gamma$ depends on assumptions about the (two-body) $\pi\pi$ interactions*).

A possible asymmetry arises in $\pi^+\pi^-\gamma$ decays, from interference between the C-conserving ($I_{\pi\pi} = 1$, $J_{\pi\pi} = 1$) amplitude and the C violating ($I_{\pi\pi} = 0$, $J_{\pi\pi} = 2$) amplitude.

A calculation has been made by Barrett and Truong$^{32)}$ using dispersion relations, and assuming the resonant ρ^0 and f^0 behaviour to determine -- even at low energies -- the $\pi\pi$ P- and D-waves respectively. A further assumption is needed about the relative magnitude (r), of the C-conserving and the C-violating amplitudes.

Within the validity of these assumptions the upper limit of the asymmetry for the η^0 is 1.1% and for the X^0 18%. These results are reduced to 0.04% and 1.4% respectively if one takes $r \simeq 1$.

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*) In fact the situation of the X^0 is even worse. See footnote to page 20.

The most significant experimental result existing for the η^0 asymmetry is[31])

$$A_{\pi\pi\gamma} = +1.5 \pm 2.5\% \qquad (40)$$

As in the $\eta \to 3\pi$ case, this result excludes large asymmetries, but, due to the model dependence of the calculations, its interpretation is not unambiguous. Also, the precision is smaller than for result (39).

We want to stress that, in the $\pi^+\pi^-\gamma$ case, the C-violating amplitude corresponds to a $\Delta I = 0$ transition, so that result (40) is in principle an indication against the presence of a K^S_μ component only. From this point of view, the $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^0 e^+ e^-$, on the one hand, and the $\eta \to \pi^+\pi^-\gamma$ on the other, are complementary experiments.

Altogether, the existing data on the three-decay modes give negative indication for both the possible hypotheses on the isospin structure of K_μ. While it would certainly be important to obtain higher precisions on the same processes, it must be stressed that, apart from the search for an electric dipole moment of the neutron*), these three decays are the only places which have been explored with careful experiments in search of a C-violating H_γ. A depression of the effect could occur in these particular processes. Thus, detailed data on other reactions would be very welcome.

The present experimental knowledge of the asymmetries in the $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ decays can certainly be improved**), at least by an increase of statistics. A parallel reduction of the level of systematic errors is perhaps less obvious.

A study of the $X^0 \to \pi^+\pi^-\gamma$ process, at least with the technique used in the experiment[31]) seems quite difficult due to the high level of the background and the low X^0 cross-section[34]).

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*) See Section 2.7.

**) A spark chamber experiment of a Columbia group is going on at Brookhaven, with this aim[33]).

The existence of the decay modes $\eta^0 \to \pi^0\pi^0\gamma$ or $X^0 \to \pi^0\pi^0\gamma$ would be a definite proof of C violation.

Their possible rates have been computed by Barrett and Truong[32] within the same framework used for the $\pi^+\pi^-\gamma$ decays.

No data exist at present and, as for many neutral decays[*] the experiments would be quite difficult.

2.5 Weak decays of the pseudoscalar mesons

As was already pointed out (see Section 2.1), if one assumes that H_{wk} is invariant under both T and CP, and that H_γ has a large C, T non-invariant part, one can explain through second order effects in I_μ decays like $K_L^0 \to 2\pi$. To the same order in I_μ, one expects T, CP non-invariant effects in K_{e3}, in K_{e4}, and in $K^0 \to \pi^+\pi^-\pi^0$. The T non-invariant amplitudes should however be smaller by about a factor α than the T-invariant ones[**].

The situation can a priori be different for first-order processes in I_μ, such as the radiative decays $K \to n\pi + \gamma$, or also for the higher order process $K^0 \to \gamma\gamma$.

The following points are of interest.

a) A comparison between the rates Γ_γ^+, Γ_γ^- of the decays

$$K^+ \to \pi^+\pi^0\gamma \tag{41}$$

and

$$K^- \to \pi^-\pi^0\gamma\ . \tag{42}$$

b) The observation of an interference term in the time distribution of K_L and K_S decays, for radiative modes, such as

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[*] For example, the separation of the $\eta \to 3\pi^0$ and $\eta \to \pi^0\gamma\gamma$ decays turns out to be delicate.

[**] In general, the expected effects are smaller here than in various models of class (c).

$$K^0 \to \pi^+\pi^-\gamma \qquad (43)$$

and also

$$K^0 \to \gamma\gamma \, . \qquad (44)$$

A difference between the rates Γ^+_γ and Γ^-_γ would be a proof of CP violation[35]. The present data on Γ^+_γ and Γ^-_γ [36] are compatible with the processes (41) and (42) being due to inner bremsstrahlung only, but they do not exclude direct γ emission to be comparable in magnitude with the bremsstrahlung contribution.

Now, inner bremsstrahlung cannot give rise to T-violating effects, whereas direct emission can. Thus, point (a) may become of interest, if a comparison of the rates is done for events surviving a cut on the low-energy part of the γ spectrum (most of the bremsstrahlung contribution is eliminated in this way).

Point (b) has been treated recently by Sehgal and Wolfenstein[37]. They show that interference between K^0_L and K^0_S decays in reactions (43) and (44) would be a direct proof of CP violation*).

$K^0_S \to \pi^+\pi^-\gamma$ decay probably occurs through the CP-conserving inner bremsstrahlung process[38] and K^0_L may possibly decay also through a CP-violating direct emission.

Thus, also for reaction (43) it is important to eliminate those events where a low-energy γ is emitted (when decreasing the γ energy, the K^0_S inner bremsstrahlung contribution — owing to the infra-red divergence — becomes much larger than the one of K^0_L, and the interference effect is rapidly decreased).

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*) The result of Sehgal and Wolfenstein is valid not only for modes (43) and (44), but also for any other non-leptonic decay mode, in particular $K^0 \to 3\pi$. Due to CP violation, K^0_S can now decay into 3π final states having the same quantum numbers as those generated in K^0_L decay — in particular CP = -1 states. However, if H_γ is responsible for C violation, the ratio of the interfering amplitudes is $\sim \alpha$ for the $K^0 \to 3\pi$ case.

2.6 Decays of the vector mesons

An essential point is that the main decay modes of all the vector mesons occur through strong interactions. Thus, possible effects of electromagnetic origin are strongly reduced in the main, non-radiative modes.

Radiative decays such as

$$\Phi^0 \to \omega^0 + \gamma \tag{45}$$

$$\Phi^0 \to \rho^0 + \gamma \tag{46}$$

$$\omega^0 \to \rho^0 + \gamma \tag{47}$$

do violate C invariance, and branching ratios of ~ 2% have been computed, for example by Bernstein et al.4) for reactions (45) and (46) on the hypothesis of strong C-violation; reaction (47) should be very low.

The difficulty may arise here from the fact that one has to deal with a relatively rare phenomenon, which may be difficult to separate experimentally from the background coming from the main decays.

This may also be true for a possible study of the $\pi^+\pi^-$ asymmetry in $\pi^+\pi^-\gamma$ decays:

$$\Phi^0 \to \pi^+\pi^-\gamma \tag{48}$$

$$\omega^0 \to \pi^+\pi^-\gamma \tag{49}$$

$$\rho^0 \to \pi^+\pi^-\gamma \,. \tag{50}$$

Radiative processes such as

$$p\bar{p} \to \pi^+\pi^-\gamma \tag{51}$$

would be very interesting, but again it is very difficult to isolate them from the main reactions, at least with the present techniques.

2.7 Electric dipole moment of the neutron

If P and T are violated, an electric dipole (EDM) moment of the baryons can exist. It has been pointed out by Feinberg$^{9)}$ that an experimentally detectable neutron EDM could be generated by the combined effect of the K_μ current and of a hypothetical weak, P-violating, $\Delta S = 0$, four-baryon interaction.

If such an interaction exists, with a coupling constant comparable in magnitude with that of the β decay, then one would expect an EDM of the neutron d:

$$d \simeq e \cdot G_V \cdot m_P \simeq 10^{-19}\ \mathrm{cm} \cdot e\ ^{*)} .$$

The above-mentioned value of d is comparable in magnitude to the presently published experimental upper limit: $d \lesssim 5 \times 10^{-20}$ $^{39)}$.

However, experiments are now going on at Brookhaven and Oak Ridge, with sensitivities of the order of $\sim 3 \times 10^{-22}$. At such a low level -- even if an effect is found, its interpretation in terms of a C-violating H_γ may turn out to be difficult (difficulties would result from the weak interactions involved).

2.8 Nuclear physics

For data in this field we refer the reader to a letter by Henley and Jacobson$^{40)}$, where further references can be found.

We just mention here as an example an experiment by Tanner et al.$^{41)}$ going on at Oxford$^{**)}$. They are comparing the differential cross-sections in reactions

$$^{16}O\ (\gamma, \alpha)\ ^{12}C \tag{52}$$

and

$$^{12}C\ (\alpha, \gamma)\ ^{16}O\ . \tag{53}$$

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*) On simple arguments of size: $d \sim 1/m_P \cdot e \simeq 10^{-14}\ \mathrm{cm} \cdot e$. A factor $\sim G_V \cdot m_P^2 \simeq 10^{-5}$ is related to the weak interaction coupling constant.

**) The experiment is carried on at Van de Graaf energies, for example, $E_\gamma \simeq 15$ MeV.

Any difference in forward-backward asymmetry in the angular distributions of the two processes, would prove T violation. In this way one is free from absolute cross-section measurements. As already said, this kind of experiment is a sensitive test of T, only to the extent that nucleons in the nucleus are out of the mass shell. A rough estimate of the maximum possible effect may be given by the ratio of the potential energy (V) of a nucleon, to its mass M:

$$V/M \sim 50/940 \sim 5 \times 10^{-2} .$$

3. EXISTING EXPERIMENTS ON η DECAY

3.1 General review

As already mentioned, most of the present data on a possible C, T violation in H_γ, concern the various η decay modes -- apart from possible new results on the EDM of the neutron (which is treated in separate lectures).

For the $\eta^0 \rightarrow \pi^0 e^+ e^-$ decay mode there is agreement among the various experimental results and we do not insist on them. We only mention here that they are obtained mostly with heavy liquid bubble chambers. Electrons are detected in the classical way due to their "spiralization" in the chamber (or their secondary bremsstrahlung pairs).

The situation of $\eta \rightarrow \pi^+\pi^-\pi^0$ decay is more involved. Table 2 reproduces the results, as they were presented in the report by Fitch at Berkeley$^{5)}$. Their order is the same in which they appeared in time. Immediately after it was realized$^{42)}$ that the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay was one of the most interesting processes to be explored, a compilation$^{43)}$ was undertaken, using previous experiments. About 10 different H_2 chamber experiments were included, with events produced in a variety of reactions (and incident energies).

The background of events different from $\eta \rightarrow \pi^+\pi^-\pi^0$ decay varied from one experiment to the other, from a lower value of 0.02 up to 0.52.

Also a correction was necessary in part of the experiments to take into account an ambiguity between the secondary π^+ from the η, and another $\pi^\pm$ produced in association with the η (for example, the π^+, in $\pi^+ + p \rightarrow p + \pi^+ + \eta$).

The net result is a global asymmetry of 5.8 ± 3.4.

On the other hand, on the hypothesis that C violation simply occurs either in $\Delta I = 0$ or in $\Delta I = 2$ transitions, asymmetries at two and at one standard deviation, respectively, are obtained.

All the experiments which followed the compilation were planned to search for an asymmetry. Thus, all of them have a low background level, and many checks have been made. In particular, for the Columbia - Stony Brook group[44)], no $\pi^+\pi^-$ asymmetry was found in a previous experiment on $\omega \rightarrow \pi^+\pi^-\pi^0$ decay, indicating the absence of biases due to the chamber and the computer programs.

The combination of their result -- a 2.5 standard deviation effect on the global asymmetry -- and of the one of the compilation[*)], was considered by the Columbia - Stony Brook group as being evidence for C violation. This indication, reinforced also by a Duke[45)] result, was not confirmed by the Rutherford - Saclay[46)] experiment and by the large statistics CERN - Zürich - Saclay experiment. Thus, at present, there is no convincing evidence for C violation.

In the next section we describe in detail some aspects of the CERN - Zürich - Saclay experiment, both because its result is the most significant one and also because its technique (spark chambers), is the only one capable of giving high statistics (it would take an enormous effort to improve the present statistics with bubble chambers).

3.2 The CERN - Zürich - Saclay experiment

The basic problems of this experiment were:

a) to obtain a high statistics,

b) to reduce the background level as much as possible,

c) to obtain a high measurement precision, and

d) to eliminate systematic errors due either to the instrument or the computer programs -- in this case possible spurious asymmetries.

Condition (b) obviously is partially related to (c). The solution of problems (a) and (b) is made relatively easy, due to the fast growth of the η production cross-section, σ_η, near its threshold. At 713 MeV/c, σ_η is already quite high (2 mb), and, due to their small c.m. momentum, the neutrons

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[*)] the two asymmetries having the same sign.

are still produced in a small laboratory cone ($\sim 13^\circ$). The neutron detection system can, therefore, be quite compact and still have a very large c.m. acceptance.

If, moreover, one puts the neutron detectors near the maximum allowed angle in the laboratory, the conditions for a "Jacobian peak" are verified -- i.e. a very small polar angle interval in the lab. ($\sim 2^\circ$ in this case) corresponds to a very large c.m. polar angle ($\sim$ 0.4 - 0.5 of the total in this case). The acceptance for neutrons associated to any other reaction different from η production is quite small. At the same time, the fact of working near the threshold of reaction $\pi^- p \rightarrow \pi^- \pi^+ \pi^0 n$ gives rise to a low contribution from this particularly dangerous background reaction.

All this greatly helps to solve problems (a) and (b). A schematic drawing of the set-up is shown in Fig. 6. The centres of the 14 neutron counters lie on a cone surface, whose opening angle coincides with the maximum angle allowed to the neutrons by the kinematics.

A time-of-flight technique allows one both to "trigger" the spark chamber when a neutron in the kinematically allowed momentum interval ($350 \leq p \leq 500$ MeV/c) hits one of the counters, and to measure with good precision ($\sim$ 0.5 nsec) the time-of-flight of the neutron associated to each event (the direction being determined by the position of each counter).

A system of counters ($\bar{A}, \bar{R}, F$) surrounding the H_2 target ensures that only events where both the secondary pions are produced in the forward direction can trigger the spark chamber system. This condition reduces the number of useless triggers.

The H_2 target is placed in a magnet and is followed by a magnetic spark chamber system[47)], which allows an accurate measurement of the secondary pion tracks [point (c)].

The events are accepted at scanning where the number of spark-chamber gaps traversed by both the positive and negative secondary tracks is larger than eight. This condition ensures a good measurement precision (the mass resolution --Fig. 7-- is even better than in H_2 chamber experiments). The only non-measured (missing) quantities are those relative to π^0's or γ's.

Events surviving the scanning conditions (32,000 over ~ 300,000) are then directly measured by H.P.D. (due to the simple and well defined topology no pre-measurement is needed) and passed in a (slightly modified) Thresh geometry program. One can then proceed to the kinematical analysis of the events. The two samples of $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ events are defined by simple cuts on the two missing masses squared MN^2 *) (Fig. 8) and MO^2 *) (Fig. 7). Figure 8 clearly shows the separation of the η sample from the background peak coming from reaction $\pi^- + p \to \pi^-\pi^+ n$ (the peak at $MN^2 = 0.88$ corresponds to MN^2 = neutron mass squared), when a cut for $MN^2 > 0.98$ is applied.

Figure 7 shows that a separation between the $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$ samples is possible, when cutting at $MO^2 = 0.006$.

The peaks corresponding to $MO^2 = m^2_{\pi^0}$ and $MO^2 = m^2_{\gamma}$ are clearly visible.

Part of the background [point (b)], is connected with η production: for example electron pairs (from internal or external conversion of γ's) coming from neutral decay modes of the η. Electron pairs are largely eliminated by a cut on the effective mass $M_{e^+e^-}$. This background, as well as contamination (~ 1%) from $\eta \to \pi^+\pi^-\gamma$ or $\eta \to \pi^+\pi^-\pi^0$ associated to an "accidental" neutron, are essentially charge symmetric.

The problem of evaluating the background coming from reactions different from η production (and possibly charge asymmetric) has been solved by running the experiment <u>also</u> at a momentum slightly lower (by ~ 28 MeV/c) than the nominal one. In this condition the maximum neutron angle is lower than the one subtended by the N counters and the triggers corresponding to η production are suppressed. The detection conditions for the other reactions are essentially unchanged, so that one can measure which amount of the background reactions is accepted <u>after</u> the cuts on MN^2 and MO^2. This background comes out to be ~ 0.5%.

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*) MN^2 is the missing mass (squared) to the two charged particles assumed to be π^+ and π^-. MO^2 is the neutral missing mass (squared) corresponding to the hypothesis $\pi^- + p \to \pi^+\pi^- n$ + neutrals.

This proves that problem (b) has a satisfactory solution.

Problem (d) is typical of this kind of spectrometer. It arises from the fact that a part of the possible laboratory configurations is not accepted by the instrument. For a given sign of the magnetic field, this may favour configurations whose average $\langle E_{\pi^+} \rangle$ is higher -- or lower -- than the average $\langle E_{\pi^-} \rangle$, thus introducing a spurious asymmetry. A similar effect can also be introduced by a systematic deformation of the events, due to a (systematically) wrong measurement of some quantity.

It is however clear that this kind of effect can be eliminated if one is able to reverse the sign of the magnetic field (this was done periodically), thus interchanging exactly the geometrical behaviour of π^+ and π^- tracks in the spark chambers. In this case, one has to take as a net result of the experiment only the average of the results corresponding to the two opposite field signs[*].

It should be noted also that, when planning the experiment, the neutron counters were placed as near as possible to the symmetry plane of the apparatus, so that the angles of the neutrons (and thus of the η's) with respect to this plane were quite small. This resulted in small intrinsic instrumental asymmetries, as is indicated by the difference between the results corresponding to the two field signs

$$A\downarrow = (1.0 \pm 1.4)\% \qquad A\uparrow = (-0.4 \pm 1.4)\% .$$

Finally, the sensitivity of the result to a wrong estimation of any parameter was computed by means of a Monte Carlo. In particular, the result was shown not to be sensitive to the incident momentum, to the value of the magnetic field and to the measured neutron momentum. Also the sensitivity to a systematic shift on the assumed azimuth of the incident π^- was found not to be critical.

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*) To change the field sign, one had to correct, correspondingly, the trajectories of the incoming π^-. This was obtained with the help of two supplementary magnets, upstream with respect to the target.

The study of the asymmetry in $\eta \to \pi^+\pi^-\gamma$ decay follows closely the one of $\eta \to \pi^+\pi^-\pi^0$. Two remarks have to be made however.

i) The intrinsic acceptance of the apparatus is a decreasing function of M^{+-}, the effective mass of the π^+ and π^- (which can be larger in this case than in $\eta \to \pi^+\pi^-\pi^0$ decay). Thus, the sensitivity of the experiment at large M^{+-}, or small c.m. P_γ values is decreased to a large extent (P_γ is the c.m. momentum of the γ).

ii) To eliminate the background from reaction $\pi^- p \to \pi^+\pi^- n$, one has to introduce a cut on the quantity MN^2 at 1.05 $(\mathrm{GeV}/c)^2$, which eliminates the remaining events with a low P_γ.

Thus, if a possible effect is substantially large for high M^{+-}, it would tend to escape observation in this experiment.

Acknowledgements

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APPENDIX

SOME VERY RECENT EXPERIMENTAL RESULTS

(The data listed in this Appendix appeared
after the publication of the previous notes)

1) K^o_S and K^o_L decays

Several new data are now available; for a compilation see the report by L.B. Okun and C. Rubbia at the 1967 Heidelberg Conference (to be published).

2) Upper limit of T non-conservation in the reactions $^{24}Mg + \alpha \rightleftarrows {}^{27}Al + p$

- W. von Witsch et al. [Phys.Rev.Letters 19, 524 (1967)].

The upper limit quoted for the ratio of T-non conserving to the T-conserving part of the reaction amplitude is: 4×10^{-3} with a confidence level of 85%.

3) EDM of the neutron

- P.D. Miller et al. [Phys.Rev.Letters 19, 381 (1967)].

  $d = (-2 \pm 3) \times 10^{-22}$ cm × e.

- C.G. Shull et al. [Phys.Rev.Letters 19, 384 (1967)]

  $d = (+2.4 \pm 3.9) \times 10^{-22}$ cm × e.

4) Charge asymmetry in the $\eta \rightarrow \pi^+\pi^-\pi^o$ decay

The data of the CERN-ETH-Saclay experiment have been recently analysed in more detail. The Dalitz plot density distribution relative to 7170 $\eta \rightarrow \pi^+\pi^-\pi^o$ events has been corrected for the effects of the background and of the efficiency. A fit with a matrix element of the form:

$M = 1 + \alpha y + \beta y^2 + \gamma x^2 + \delta x$ gives: $\delta = 0.006 \pm 0.013$, with a χ^2 of 115.9 for 116 degrees of freedom. The possible presence of a $\Delta I = 2$, C-violating amplitude is now quantitatively expressed by the value of δ.

In a similar way, a fit with a matrix element of the form: $M = 1 + \alpha y + \beta \cdot y^2 + \gamma \cdot x^2 + \delta \cdot (3y^2 - x^2)\, x$ allows one to establish an upper limit for a possible $\Delta I = 0$ amplitude. The result is $\delta = 0.00 \pm 0.02$ with a $\chi^2 = 116.1$, for 116 degrees of freedom.

REFERENCES

1. J.H. Christenson et al., Phys.Rev. 13, 138 (1964).

2. J. Prentki, Rapporteurs talk, in Proc. Oxford Int. Conference on Elementary Particle Physics, 1965 (Rutherford High Energy Laboratory, Chilton, Didcot, 1966).

3. J. Prentki and M. Veltman, Physics Letters 15, 88 (1965); and also Preludes in theoretical physics (North Holland, Amsterdam 1966), p. 250.

4. J. Bernstein, G. Feinberg and T.D. Lee, Phys.Rev. 139B, 1650 (1965).

5. V.L. Fitch, Rapporteurs talk, in Proc. 13th Int. Conference on High Energy Physics, Berkeley, 1966 (Univ. of Calif. Press, Berkeley, 1967), p. 63.

6. J.M. Gaillard et al., Phys.Rev.Letters 18, 20 (1967); and J.W. Cronin et al., Phys.Rev.Letters 18, 25 (1967).

7. C. Baltay et al., Phys.Rev.Letters 15, 951 (1965).

8. L. Dobrzinski et al., Physics Letters 22, 105 (1966).

9. N. Cabibbo, Phys.Rev.Letters 14, 965 (1965); and G. Feinberg, Phys.Rev. 140B, 1402 (1965).

10. L. Rosen and J.E. Brolley, Phys.Rev.Letters 2, 98 (1959); and D. Bodansky et al., Phys.Rev.Letters 2, 101 (1959).

11. W. von Witsch et al., Physics Letters 22, 631 (1965); a quite sensitive experiment is now being continued at Heidelberg along these lines.

12. A. Abashian and E.M. Hafner, Phys.Rev.Letters 1, 255 (1958).

13. See for example the lecture notes by E. Picasso, at this school.

14. N. Christ and T.D. Lee, Phys.Rev. 143, 1310 (1966).

15. F. Hadjioannou et al., Preprint (1966).

16. N. Christ and T.D. Lee, Phys.Rev. 148, 1520 (1966).

17. S. Barshay, Phys.Rev.Letters 17, 49 (1966).

18. N. Cabibbo and M. Veltman, CERN 65-30 (1965).

19. C.A. Picketty, Orsay preprint 1965.

20. Björken and Walecka, SLAC preprint 139/1966.

21. R. Kose, Thesis, University of Bonn, 1966.

22. D. Measday (private communication).

23. T.D. Lee, Phys.Rev. **139B**, 1415 (1965); Phys.Rev. **140B**, 959 (1964); Phys.Rev. **140B**, 967 (1965).

24. V. Soergel et al., Physics Letters **19**, 253 (1965).

25. C. Bemporad et al., CERN Seminar 1967.

26. Result by an English collaboration (University College et al.), M. Esten (private communication); a value of 0.9×10^{-3} has been obtained by Baglin et al., Ecole Polytechnique preprint May 1967.

27. T.D. Lee, Phys.Rev. **139B**, 1415 (1965).

28. See, for example, T.D. Lee, Rapporteurs talk, in Proc. 13th Int. Conference on High Energy Physics, Berkeley, 1966 (Univ. of Calif. Press, Berkeley, 1967), p. 75.

29. A.M. Cnops et al., Physics Letters **22**, 546 (1966).

30. See, for example, O. Skieggestad, 1964 Herceg Novi School (CERN 64-13), for general symmetry properties of the 3π states. Detailed arguments about $\eta \to 3\pi$ decay are found in Refs. 3 and 29.

31. R. Bowen et al., Physics Letters **24B**, 206 (1967).

32. B. Barrett and T. Truong, preprint 1966.

33. W. Lee (private communication).

34. J.P. Dufey et al., CERN preprint 1968.

35. See, for example, G. Costa and P. Kabir, Rutherford Lab. preprint 1967.

36. D. Cline and W. Fry, Phys.Rev.Letters **13**, 101 (1964).

37. Sehgal and Wolfenstein, preprint 1967.

38. B. Aubert et al., Proc. Sienna Int. Conference on Elementary Particles, 1963 (Bologna, Società Italiana di Fisica, 1963) vol. 1, p. 20; and P. Franzini et al., Phys.Rev. 140B, 127 (1965).

39. J.H. Smith, E.M. Purcell and N.F. Ramsey, Phys.Rev. 108, 120 (1957).

40. Henley and Jacobson, Phys.Rev.Letters 16, 706 (1966).

41. J. Domingo (private communication).

42. Friedberg, Lee and Schwartz (unpublished).

43. C. Baltay et al., UCRL - 16693.

44. C. Baltay et al., Phys.Rev.Letters 16, 1224 (1966).

45. Fortney et al. (see ref. 5).

46. Saclay-Rutherford Laboratory Collaboration (see ref. 5).

47. P. Astbury et al., Nucl.Instrum. Methods 46, 61 (1967).

Table 1

Tests of TCP

Particles	Measured quantity	Value	Reference
μ^+, μ^-	lifetimes	0.000 ± 0.001	Meyer et al.
K^+, K^-	$\frac{\tau_+}{\tau_-} - 1$	-0.0009 ± 0.0008	Lobkowicz et al.
π^+, π^-	same	0.004 ± 0.0018	Lobkowicz et al.
π^+, π^-	same	0.004 ± 0.007	Bardon et al.
π^+, π^-	same	0.0056 ± 0.0028	Ayres et al.
$K^0, \bar{K}^0$	mass equality	2 parts in 10^{16}	
e^+, e^-	gyromagnetic ratios $\frac{1}{2}(g^+ - g^-)$	$(1.5 \pm 2) \frac{\alpha^2}{\pi^2}$	Rich and Crane
μ^+, μ^-	same	$(0 \pm 1.5) \frac{\alpha^2}{\pi^2}$	CERN

Table 2

Compendium of η-decay results

	Reference	Total no. η	Sextants						+	–	Asymmetry (%)
			1	2	3	4	5	6			
Compilation	1	1300	119	199	361	298	205	101	679	604	5.8 ± 3.4
Columbia - Stony Brook	2	1351	100	239	385	340	196	91	724	627	7.2 ± 2.8
Duke	3	565	42	76	176	162	78	31	294	271	4.1 ± 4.1
Rutherford - Saclay	4	705	54	126	151	174	139	61	331	374	-6 ± 4
CERN - Zürich - Saclay	3	10665	1511	1850	2027	2050	1821	1489	5388	5360	0.3 ± 1.0

Figure captions

Fig. 1 : Feynman diagram for the electroproduction of the resonances.

Fig. 2 : Diagram of Barshay for the reaction $\gamma + d \rightarrow n + p$.

Fig. 3 : Feynman diagram for $\eta^0 \rightarrow \pi^0 e^+ e^-$ decay.

Fig. 4 : Numbers of events per sextant in the CERN - Zürich - Saclay experiment.

Fig. 5 : The asymmetry as a function of $|T^+ - T^-|$ in the CERN - Zürich - Saclay experiment.

Fig. 6 : Schematic layout of the CERN - Zürich - Saclay experiment.

Fig. 7 : Distribution of MO^2 in the CERN - Zürich - Saclay experiment.

Fig. 8 : Distribution of MN^2 in the CERN - Zürich - Saclay experiment.

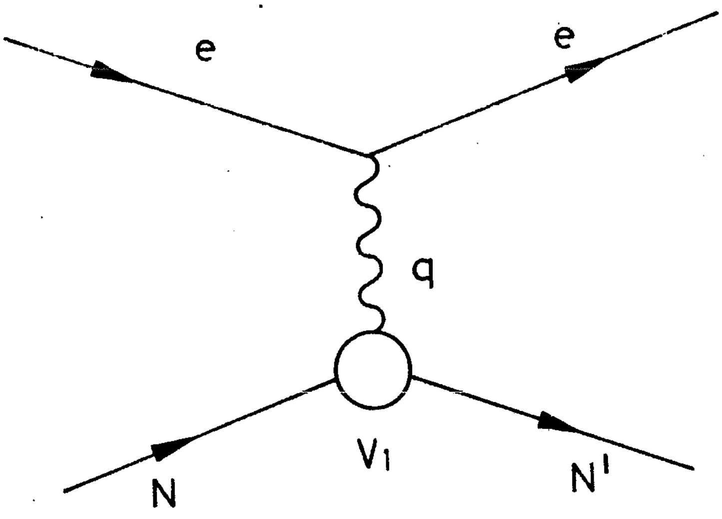


FIG.1

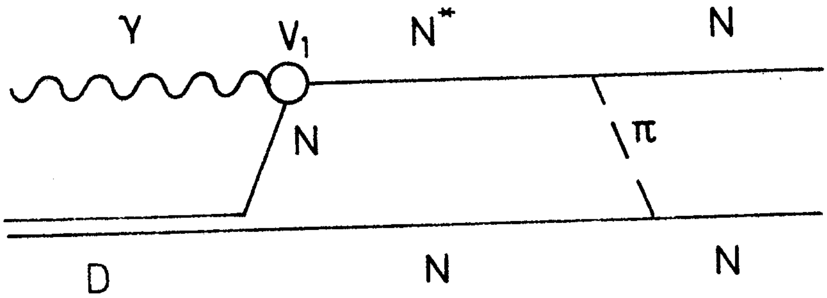


FIG.2

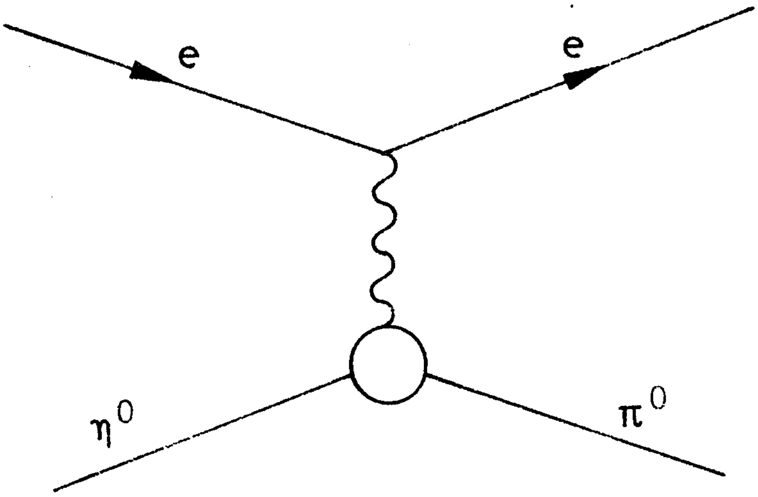


FIG.3

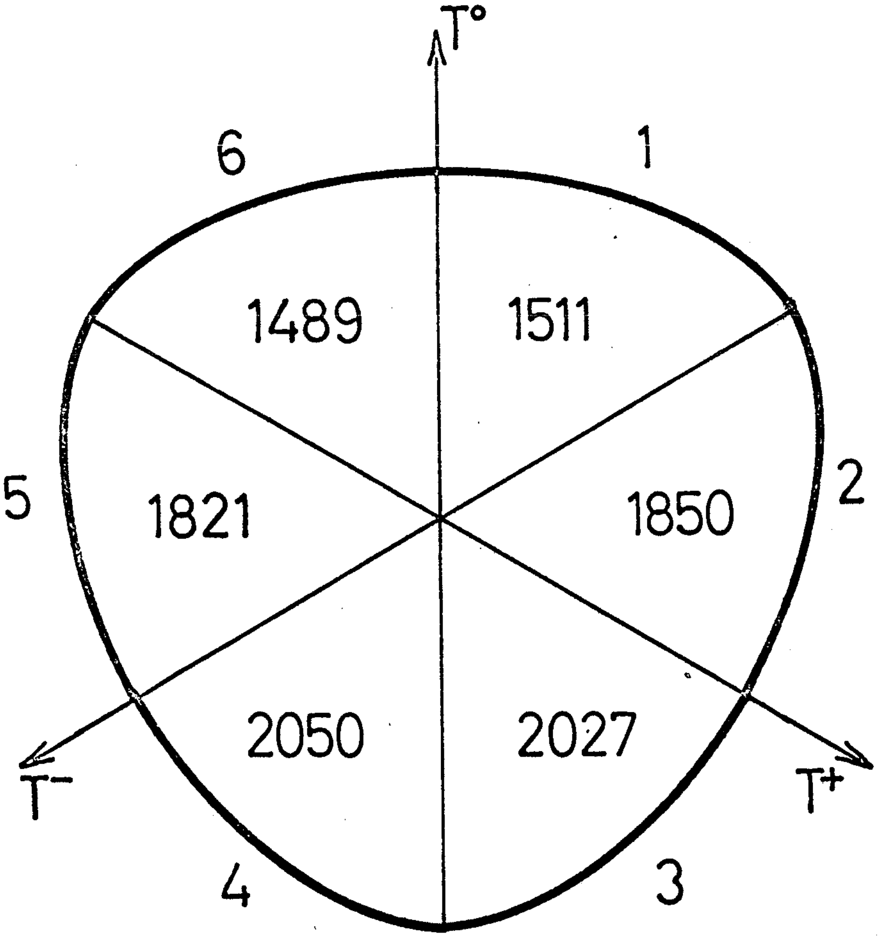


Fig. 4

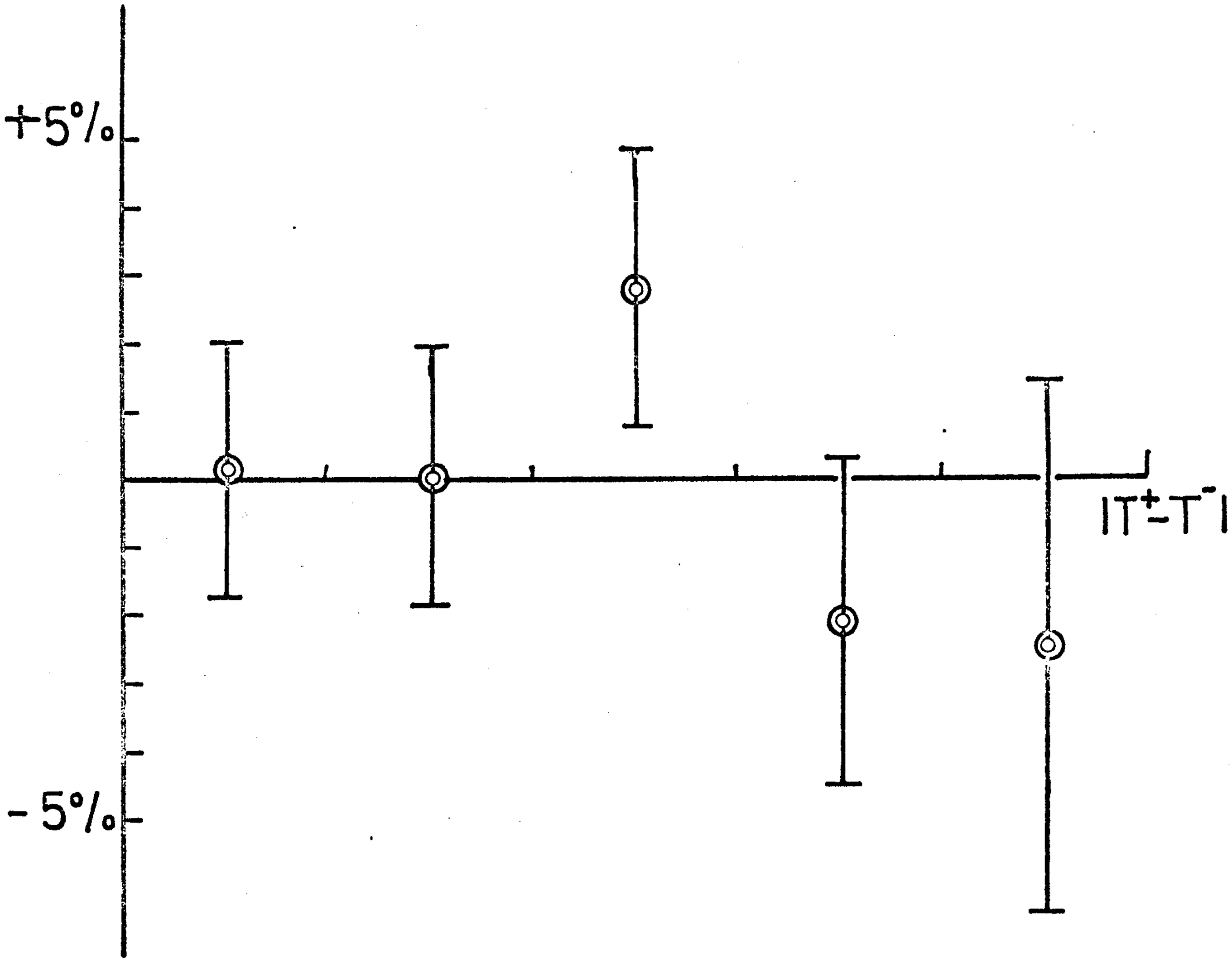


Fig. 5

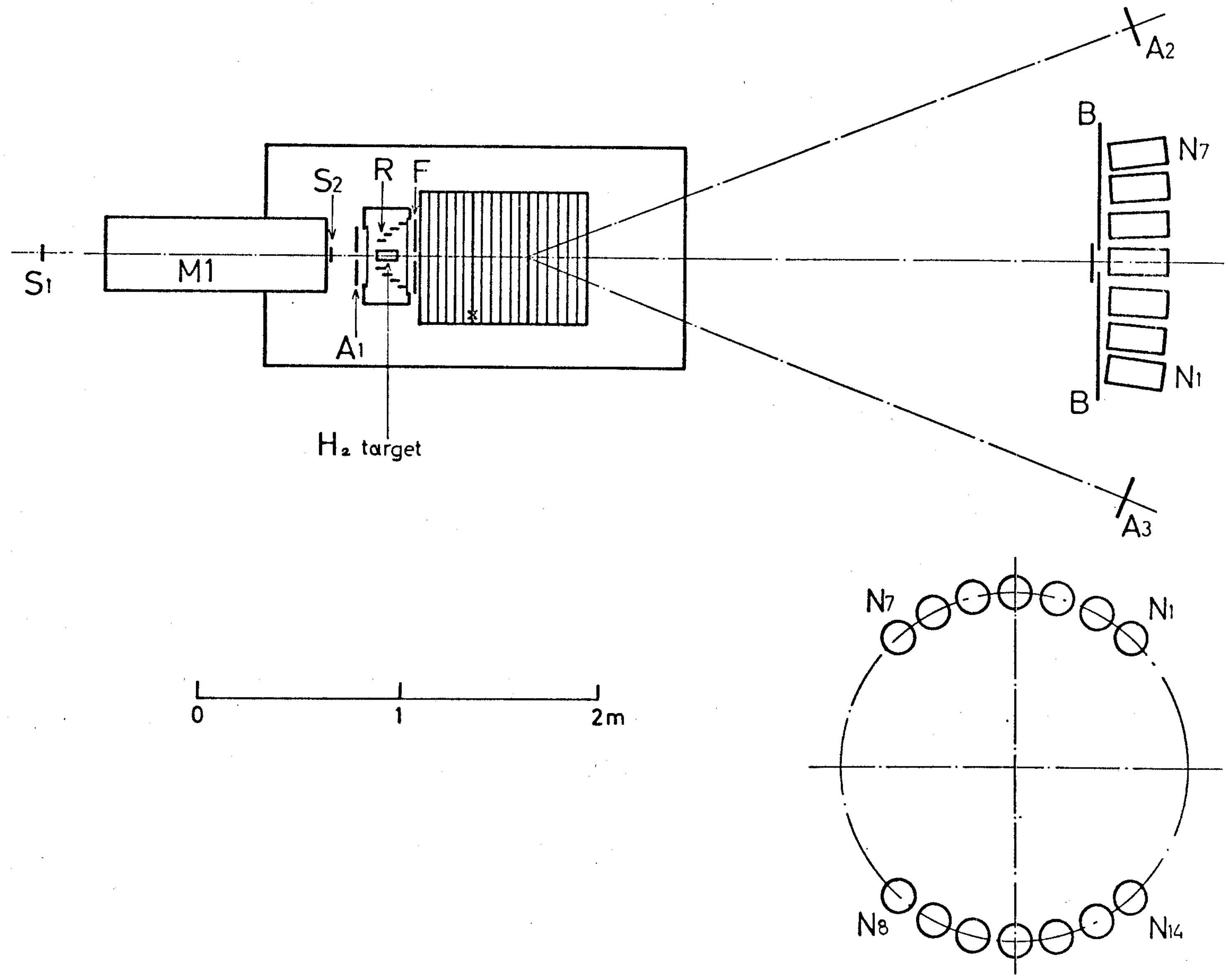
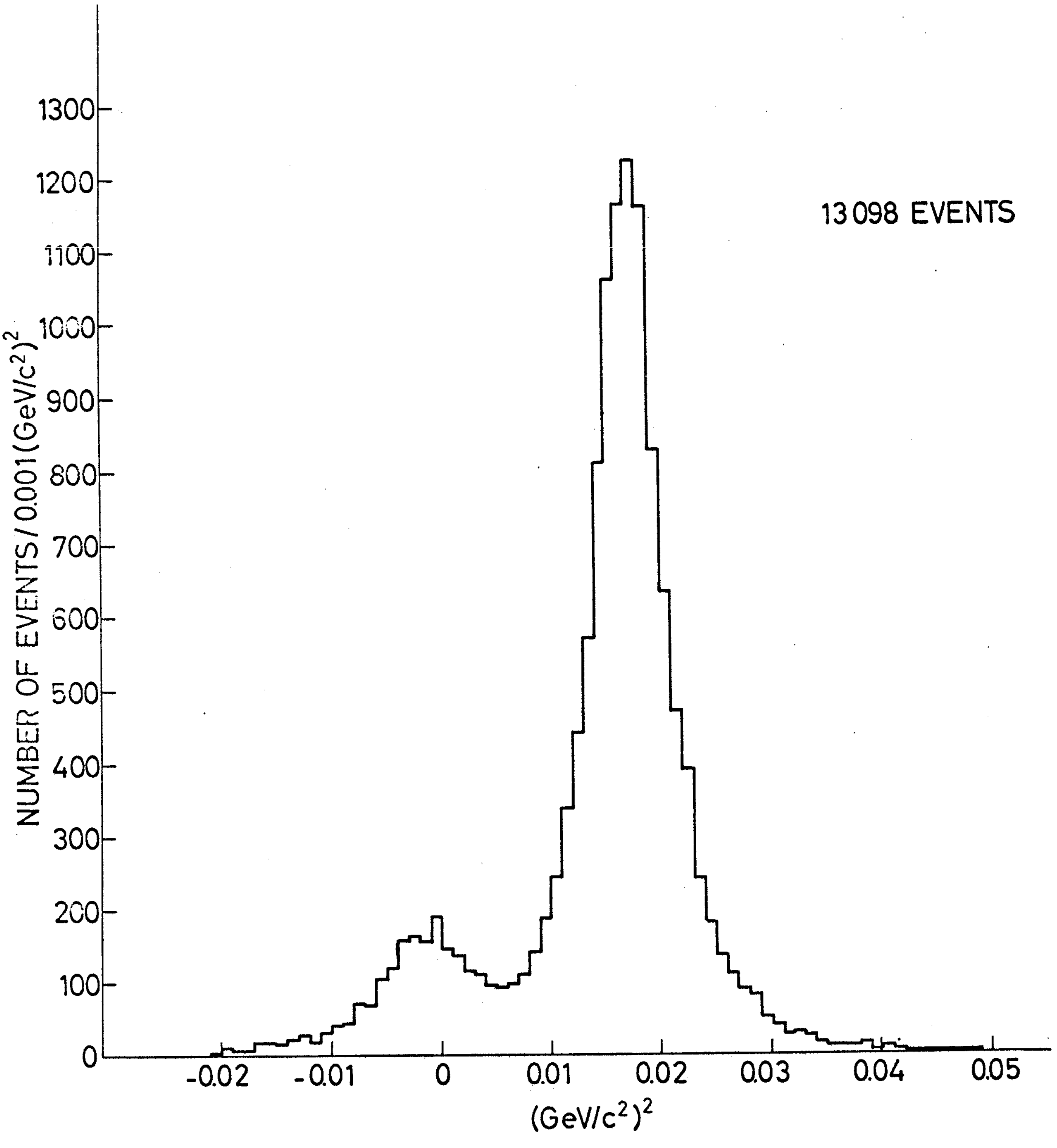


Fig. 6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300
400
500
600
700
800
900
1000
1100
1200
1300
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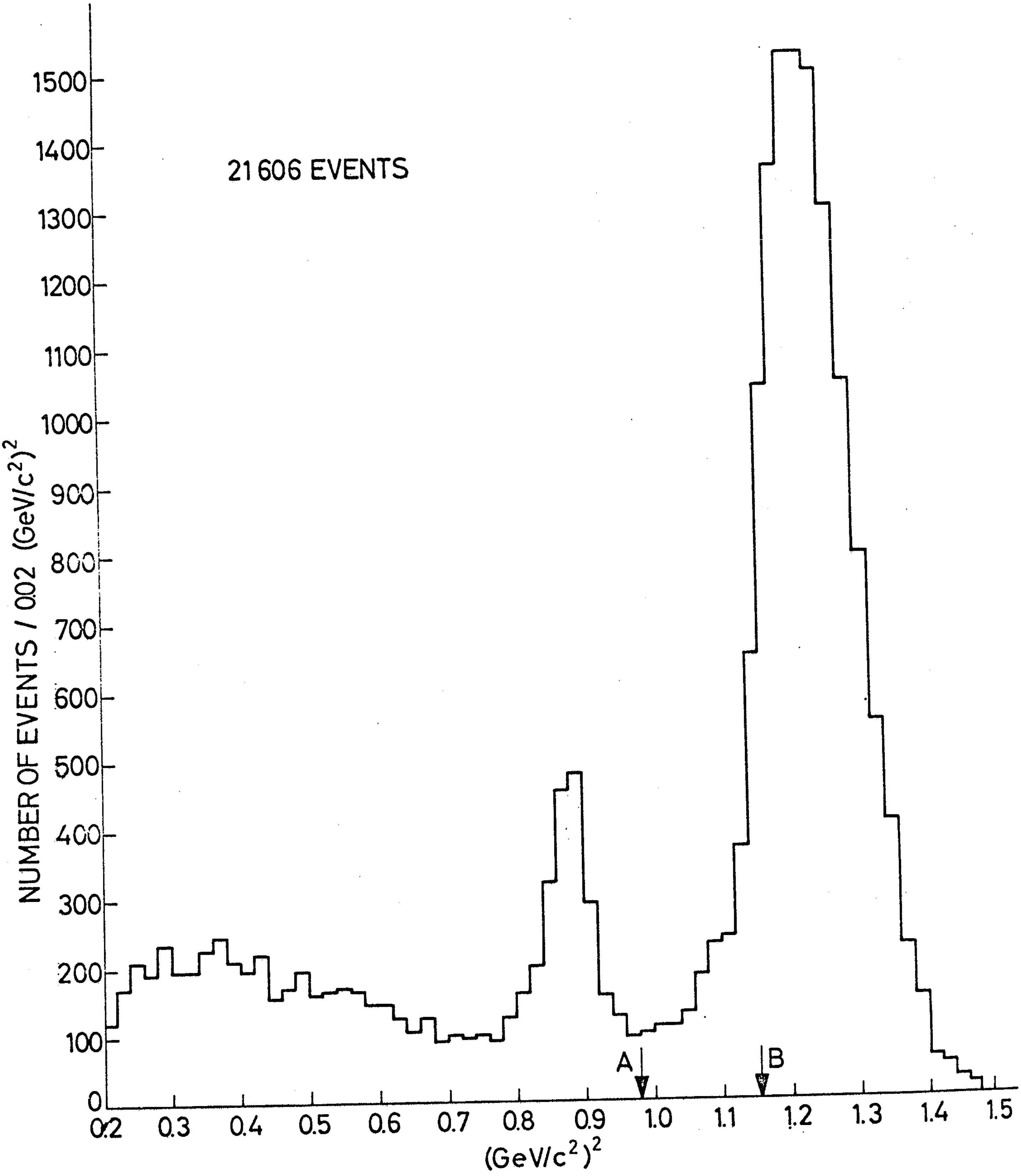
-0.01
0
0.01
0.02
0.03
0.04
0.05
(GeV/c^2)^2

Fig. 7



21 606 EVENTS
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600
700
800
900
1000
1100
1200
1300
1400
1500
A
B
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
$(GeV/c^2)^2$

Fig. 8