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POLARIZATION EXPERIMENTS AIMED AT VERIFYING T- AND CPT-INVARIANCE IN NUCLEON-NUCLEON AND NUCLEON-ANTINUCLEON SCATTERING

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Usp. Fiz. Nauk 95, 489–501 (July, 1968)

THE discovery of CP-violation in K_L^0-meson decays, and the hypotheses advanced in connection with this discovery, have led to the performance of many new experiments aimed at verifying T- and C-invariance in weak, electromagnetic, and strong interactions. We shall discuss here experiments on the verification of T-invariance in elastic nucleon-nucleon scattering. In addition, we shall consider briefly the possible experiments aimed at verifying CPT-invariance during the process of elastic scattering of antiprotons by protons.

I. VERIFICATION OF T-INVARIANCE IN EXPERIMENTS ON THE SCATTERING OF NUCLEONS

1. As is well known, the requirement that the S-matrix be invariant against time reversal leads to the following relation between the amplitudes of the direct and inverse processes:

$$\langle f|S|i\rangle = {}_T\langle i|S|f\rangle_T. \tag{1}$$

Here $|i\rangle_T$ ($|f\rangle_T$) describes the same particles as $|i\rangle$ ($|f\rangle$), but with opposite signs of the momenta and spins.

In the case of elastic scattering of particles with spin, relation (1) becomes a limitation on the possible form of the scattering amplitude, and leads to relations between the different observables pertaining to one and the same process. The experimental verification of such relations is indeed the verification of T-invariance of the scattering matrix. We note that in the case of scattering of spinless particles by particles with spin $\frac{1}{2}$, T-invariance imposes no additional limitations on the scattering matrix, provided the latter is invariant against rotations and reflections. Thus, if parity is conserved in the elastic-scattering processes $0 + \frac{1}{2} \to 0 + \frac{1}{2}$, then an investigation of such processes cannot yield any information concerning T-violation. On the other hand, in the case of elastic collisions of two particles with spin $\frac{1}{2}$, for example nucleon-nucleon scattering, as first shown in[1,2], T-invariance imposes additional limitations on the scattering matrix, which satisfies the requirements of invariance against rotations and reflections. The possible experiments on the verification of T-invariance in nucleon-nucleon scattering has been discussed in[3-5]. Here we consider the relations between the polarization characteristics of the nucleon-nucleon scattering process, which follow from T-invariance, and discuss the organization and the results of the corresponding experiments.

2. In the general case, when no invariance of the interactions under time reversal is assumed, the proton-proton scattering matrix $M(\mathbf{p}', \mathbf{p})$ ($\mathbf{p}'$ and $\mathbf{p}$ – momenta of the incident and scattered protons in the c.m.s.) can always be represented in the form

$$M(\mathbf{p}', \mathbf{p}) = M_+(\mathbf{p}', \mathbf{p}) + M_-(\mathbf{p}', \mathbf{p}), \tag{2}$$

$$M_\pm(\mathbf{p}', \mathbf{p}) = \pm (U^{-1}M_\pm(-\mathbf{p}, -\mathbf{p}')U)^T. \tag{3}$$

The unitary matrix U satisfies the relations

$$\begin{aligned}(U^{-1}\sigma_{1i}U)^T &= -\sigma_{1i},\\ (U^{-1}\sigma_{2i}U)^T &= -\sigma_{2i},\end{aligned} \tag{4}$$

where $(\frac{1}{2})\sigma_{1i}$ and $(\frac{1}{2})\sigma_{2i}$ are the nucleon spin operators, and the symbol T denotes the transpose. The requirement that the nucleon-nucleon interactions be invariant under time reversal signifies that $M_- = 0$.

Upon rotation through an angle π around the vector

$$\mathbf{m} = \frac{\mathbf{p}'-\mathbf{p}}{|\mathbf{p}'-\mathbf{p}|} \tag{5}$$

the momentum $(-\mathbf{p})$ goes over into $\mathbf{p}'$ and $(-\mathbf{p}')$ into $\mathbf{p}$, and from the invariance against rotations we obtain

$$M(-\mathbf{p}, -\mathbf{p}') = (\sigma_1\mathbf{m})(\sigma_2\mathbf{m})M(\mathbf{p}', \mathbf{p})(\sigma_1\mathbf{m})(\sigma_2\mathbf{m}). \tag{6}$$

If T-invariance holds ($M = M_+$), then it is easy to obtain directly from (3), (4), and (6) relations between the different polarization characteristics of the pp scattering process. We confine ourselves to a consideration of the relations between the polarization, asymmetry, and components of the depolarization tensor. The polarization and asymmetry vectors and the depolarization tensor are defined as follows (see, e.g.,[6]):

$$\sigma_0\mathbf{P}_i = \frac{1}{4}\,\mathrm{Sp}\,\sigma_{1i}MM^+, \tag{7a}$$

$$\sigma_0\mathbf{A}_i = \frac{1}{4}\,\mathrm{Sp}\,M\sigma_{1i}M^+, \tag{7b}$$

$$\sigma_0 D_{ik} = \frac{1}{4}\,\mathrm{Sp}\,\sigma_{1i}M\sigma_{1k}M^+, \tag{7c}$$

where σ_0 is the differential cross section of the scattering of unpolarized particles in the c.m.s.

Using the requirement of T-invariance and the invariance against rotations ($M = M_+$ and formulas (3), (4), and (6)), we get from (7)

$$P = A, \tag{8}$$

$$D_{ml} + D_{lm} = 0, \tag{9}$$

where $P = (\mathbf{P}\cdot\mathbf{n})$, $A = (\mathbf{A}\cdot\mathbf{n})$, $D_{ab} = a_i D_{ik} b_k$, and the vectors $\mathbf{l}$ and $\mathbf{n}$ are defined as follows:

$$\mathbf{l} = \frac{\mathbf{p}+\mathbf{p}'}{|\mathbf{p}+\mathbf{p}'|}, \quad \mathbf{n} = \frac{[\mathbf{p}\mathbf{p}']}{|[\mathbf{p}\mathbf{p}']|}. \tag{10}$$

If the scattering matrix is not invariant against time reversal ($M_- \neq 0$), then we obtain in lieu of (8) and (9)

$$P - A = \frac{1}{\sigma_0}\,\mathrm{Re}\,\mathrm{Sp}\,(\sigma_1\mathbf{n})\,M_+M_-^+, \tag{11}$$

$$D_{ml} + D_{lm} = \frac{1}{\sigma_0} \operatorname{Re} \operatorname{Sp} (\boldsymbol{\sigma}_1 \mathbf{m}) M_+ (\boldsymbol{\sigma}_1 \mathbf{l}) M_-^+. \tag{12}$$

We note that in deriving (11) and (12) no assumptions were made concerning P-parity conservation. The matrices $M_\pm$ can always be broken up into P-even and P-odd parts:

$$M_\pm (\mathbf{p}', \mathbf{p}) = M_\pm^e (\mathbf{p}', \mathbf{p}) + M_\pm^0 (\mathbf{p}', \mathbf{p}), \tag{13}$$

where

$$M_\pm^e (\mathbf{p}', \mathbf{p}) = M_\pm^e (-\mathbf{p}', -\mathbf{p}), \tag{14a}$$

$$M_\pm^0 (\mathbf{p}', \mathbf{p}) = -M_\pm^0 (-\mathbf{p}', -\mathbf{p}). \tag{14b}$$

Upon rotation through an angle π around the normal to the scattering plane, $(-\mathbf{p}')$ does over into $\mathbf{p}'$ and $(-\mathbf{p})$ goes over into $\mathbf{p}$. From the invariance against rotations we obtain

$$M_\pm^{e,\,0} (-\mathbf{p}', -\mathbf{p}) = (\boldsymbol{\sigma}_1 \mathbf{n}) (\boldsymbol{\sigma}_2 \mathbf{n}) M_\pm^{e,\,0} (\mathbf{p}', \mathbf{p}) (\boldsymbol{\sigma}_1 \mathbf{n}) (\boldsymbol{\sigma}_2 \mathbf{n}). \tag{15}$$

With the aid of (14) and (15) we can easily verify that the parity nonconserving matrices $M_\pm^0$ enter in the considered observables P, A, D_{ml}, and D_{lm} quadratically. The results of experiments aimed at observing the effect of parity nonconservation in nuclear reactions at low energies are compatible with the assumption that parity is conserved in strong and in electromagnetic interactions. Therefore, in expressions for the observable quantities it is reasonable to confine oneself only to terms linear in $M_\pm^0$. In this approximation, it is necessary to replace $M_\pm$ by $M_\pm^e$ in the right sides of (11) and (12).

From considerations of invariance and from the Pauli principle it follows[1,2,4-5] that

$$M_+^e = (u+v) + (u-v)(\boldsymbol{\sigma}_1 \mathbf{n})(\boldsymbol{\sigma}_2 \mathbf{n}) + c\,[(\boldsymbol{\sigma}_1 \mathbf{n}) + (\boldsymbol{\sigma}_2 \mathbf{n})]$$
$$+ (g-h)(\boldsymbol{\sigma}_1 \mathbf{m})(\boldsymbol{\sigma}_2 \mathbf{m}) + (g+h)(\boldsymbol{\sigma}_1 \mathbf{l})(\boldsymbol{\sigma}_2 \mathbf{l}), \tag{16}$$

$$M_-^e = t\,[(\boldsymbol{\sigma}_1 \mathbf{m})(\boldsymbol{\sigma}_2 \mathbf{l}) + (\boldsymbol{\sigma}_1 \mathbf{l})(\boldsymbol{\sigma}_2 \mathbf{m})]. \tag{17}$$

With the aid of (16) and (17) we get

$$P - A = \frac{1}{\sigma_0} \operatorname{Re} \operatorname{Sp} (\boldsymbol{\sigma}_1 \mathbf{n}) M_+^e M_-^{e+} = \frac{8}{\sigma_0} \operatorname{Im} th^*, \tag{18}$$

$$D_{ml} + D_{lm} = \frac{1}{\sigma_0} \operatorname{Re} \operatorname{Sp} (\boldsymbol{\sigma}_1 \mathbf{m}) M_+^e (\boldsymbol{\sigma}_1 \mathbf{l}) M_-^{e+} = \frac{8}{\sigma_0} \operatorname{Re} tg^*. \tag{19}$$

The parameters P and A are directly observable quantities. It is easy to show (see, e.g.,[6]), that the left side of (19) is connected with the known triple-scattering parameters R, R′, A, and A′[7]. Taking into account the relativistic spin flip[8], we get[6]

$$D_{ml} + D_{lm} = (R' + A) \cos \theta_l - (A' - R) \sin \theta_l, \tag{20}$$

where θ_l is the scattering angle in the l.s.

If T-invariance holds, then the parameters of the triple scattering are connected, as seen from (9) and (20), by the relation[9]

$$\frac{A + R'}{A' - R} = \operatorname{tg} \theta_l. \tag{21}$$

The amplitudes g and h, which enter in (18) and (19), are known at present from a phase-shift analysis in the energy interval up to ≈700 MeV. By the same token, comparison of (18) and (19) with the experimental data makes it possible to obtain information on the T-violating amplitude t.

Let us consider briefly the question of the parametrization of the nucleon-nucleon scattering matrix in the (J, M, l, S) representation (J, M-total angular momentum at its projection, l - orbital angular momentum, S - total spin). We shall assume now for simplicity that the parity is conserved. We denote the elements of the S-matrix in the considered representation in terms of S^J for singlet-singlet transitions and $S^J_{l';l}$ for triplet-triplet transitions* (singlet-triplet transitions are forbidden by parity conservation and by the Pauli principle). The invariance under time reversal imposes no limitations on S^J and on the diagonal elements $S^J_{l;l}$, and leads to equality of the nondiagonal elements

$$S^J_{J+1;\,J-1} = S^J_{J-1;\,J+1}. \tag{22}$$

When T-invariance is violated, Eq. (22) does not hold, but it is easy to show[10,4] that the requirement of unitarity of the S-matrix in the energy region up to the threshold of meson production leads to equality of the moduli

$$|S^J_{J+1;\,J-1}| = |S^J_{J-1;\,J+1}| \tag{23}$$

and the elements of the S matrix are parametrized in the following manner (the Stapp parametrization[11]):

$$S^J = e^{2i\delta_J}, \quad S^J_{J;\,J} = e^{2i\delta_{J,\,J}}, \tag{24a}$$

$$\left.\begin{aligned} S^J_{J-1;\,J-1} &= \cos 2\varepsilon_J e^{2i\delta_{J-1,\,J}}, \\ S^J_{J+1;\,J+1} &= \cos 2\varepsilon_J e^{2i\delta_{J+1,\,J}}, \\ S^J_{J-1;\,J+1} &= i \sin 2\varepsilon_J e^{i(\delta_{J-1,\,J} + \delta_{J+1,\,J} + \lambda_J)}, \\ S^J_{J+1;\,J-1} &= i \sin 2\varepsilon_J e^{i(\delta_{J-1,\,J} + \delta_{J+1,\,J} - \lambda_J)}. \end{aligned}\right\} \tag{24b}$$

We note that when parity is not conserved, singlet-triplet transitions appear, but the parametrization of the matrix elements written out above remains valid in the linear approximation in the parameters corresponding to parity nonconservation[5,12]. The parameter λ_J characterizes the violation of T-invariance. The maximum violation of T-invariance corresponds to a relative phase $2\lambda = \pi$ of the non-diagonal elements.

Finally, the T-violating amplitude t is expressed as follows in terms of the S-matrix elements[5,12]:

$$t = \frac{1}{4} \frac{1}{ip} \sum_{l\text{-even}} (S^{l+1}_{l;\,l+2} - S^{l+1}_{l+2;\,l}) \frac{2l+3}{[(l+1)(l+2)]^{1/2}} [(l+1) P_l(\theta) \sin\theta + P_l^{(1)}(\theta) \cos\theta],$$

$$S^{l+1}_{l;\,l+2} - S^{l+1}_{l+2;\,l} = -2 \sin 2\varepsilon_{l+1} \sin \lambda_{l+1} e^{i(\delta_{l,\,l+1} + \delta_{l+2,\,l+1})}. \tag{25}$$

3. The first experiments on the verification of T-invariance in proton-proton scattering were performed in 1958[13,14]. In these experiments the polarization P and the asymmetry A were measured independently. Before proceeding to describe these experiments, we note that in the case of elastic scattering of protons by particles with zero spin the "polarization-asymmetry" relation is the consequence of only parity conservation. This makes it possible to determine from experiments on double scattering by identical targets with zero spin the analyzing (or polarizing) ability of such targets, regardless of whether T-invariance holds or not. In the measurement of polarization in pp-scattering, a beam of unpolarized protons was scattered by a hydro-

*Owing to the Pauli principle l and l' are equal to J ± 1 when J is even and J = l = l' when J is odd.

Values of measured quantities (if T-invariance holds, then these quantities should be equal to zero)	C.m.s. angle, deg.	L.s. energy, MeV	Reference	Upper limit of phase λ_2, characterizing the violation of T-invariance
$P_0 - A_0 = -0.029 \pm 0.018$	30	210	13	
$P_0 - A_0 = 0.007 \pm 0.023$	30.9	176	14	
0.011 ± 0.022	50.0	179		
-0.043 ± 0.025	15			$\lambda_2 \leqslant 0.07 \frac{\pi}{2}$
-0.023 ± 0.023	20			
$P_0 - A_0 = 0.063 \pm 0.024$	25	142	15	
0.010 ± 0.023	30			
0.002 ± 0.048	35			
-0.083 ± 0.066	40			
0.045 ± 0.057	41.2	635	16	
$P_0 - A_0 = -0.021 \pm 0.032$	47.8			
-0.021 ± 0.035	60.8			
-0.023 ± 0.039	71.8			
$(A + R') \cos\theta - (A' - R) \sin\theta = 0.0019 \pm 0.009$	$\theta = 30°$ (θ — angle in l.s.)	430	17	$\lambda_2 \leqslant 0.06 \frac{\pi}{2}$

gen target, and was then scattered again, in the same plane, by a target with zero spin and with known analyzing ability (carbon). In the measurements of the asymmetry A, the unpolarized proton beam was first scattered by carbon, and then the scattered beam, with known degree of polarization, was scattered again by a hydrogen target. In the measurement of P, the unpolarized beam was first decelerated in order that the energy at which the scattering by the hydrogen takes place correspond to the pp-scattering energy in the experiment in which A was measured. In subsequent investigations[15,16], the "polarization-asymmetry" relation was verified in experiments on triple scattering in a single plane. The advantage of these experiments was that P and A was automatically measured in them at the same energy. The results of these experiments are listed in the table. An analysis of the results of[13-16] (energy interval from 140 to 210 MeV) was carried out in[12] and led to the conclusion that the parameter λ_2 (the parameter characterizing the violation of T-invariance in transitions ${}^3P_2 \rightleftarrows {}^3F_2$) does not exceed 0.07 of the possible maximum value $\pi/2$.

The most accurate experiment on the verification of T-invariance in pp scattering was performed recently[17]. In this experiment, relation (21) between the parameters of the triple scattering was verified at 430 MeV energy. The scheme of this experiment is shown in Fig. 1. It is obvious that the configurations

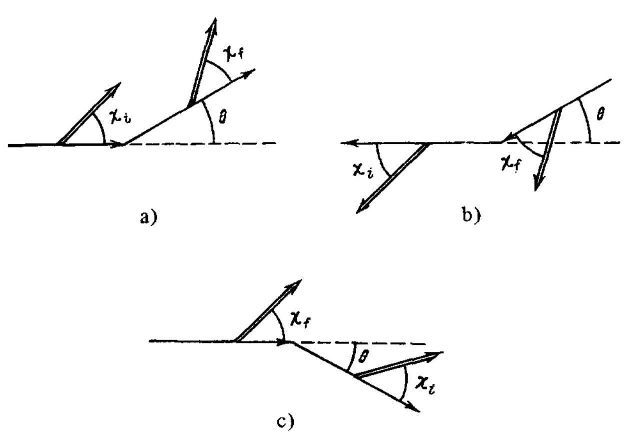

FIG. 1. Experimental scheme for verifying relation (21) between the triple-scattering parameters (in the c.m.s.). The double arrows denote the spin directions.

shown in Figs. 1b and 1a are connected by a T-transformation, and the configuration of Fig. 1c is obtained from the configuration of Fig. 1b by rotation through an angle $\pi - \theta$ around the normal to the scattering plane. If T-invariance holds, then the projections of the final polarizations on the directions indicated by the double arrows in Figs. 1a and 1c should be equal at an equal degree of polarization of the initial particles (the directions of the initial polarizations are also indicated by the double arrows).

Under a Lorentz transformation* from the c.m.s. to the l.s., the directions of the initial polarization remain unchanged, and $\chi_f \to \chi_f^l = \chi_f + \theta_l$ in the case of the configuration shown in Fig. 1a, and $\chi_i \to \chi_i^l = \chi_i - \theta_l$ for the configuration of Fig. 1c[8]. Here θ_l is the scattering angle in the l.s., and χ_i^l are the angles between the momenta of the scattered particles and those l.s. directions, the polarization projections on which should be measured in order to compare configurations 1a and 1c. The scheme of the l.s. experiments corresponding to the configurations of Figs. 1a and 1c is shown in Figs. 2a and 2b respectively.

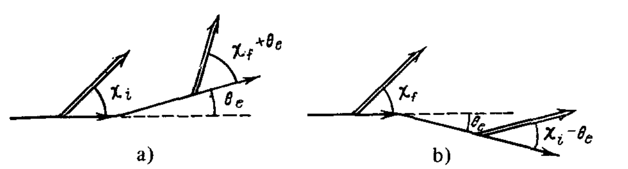

FIG. 2. Experimental scheme for verifying T-invariance in the l.s. Fig. 2a corresponds to Fig. 1a in the c.m.s., and Fig. 2b corresponds to Fig. 1c.

Let us denote by P_A and P_B the projections of the final polarizations on the directions indicated by the double arrows in Figs. 2a and 2b, in the case of a fully polarized initial beam. It is easy to see that

$$P_A - P_B = [(A + R') \cos\theta_l - (A' - R) \sin\theta_l] \sin(\chi_i + \chi_f). \qquad (26)$$

It follows therefore that the difference $P_A - P_B$ vanishes in accordance with (21) if T-invariance holds. The angles χ_i and χ_f were chosen to be equal to $\pi/4$

*In the relativistic case, the angles χ and χ^l should be taken to mean the angles between the directions of the momenta and the polarizations in the rest systems obtained from the c.m.s. and l.s. by Lorentz transformation along the corresponding momenta.

in the experiments. This ensured a maximum difference $P_A - P_B$ and made it possible to use the same polarized beam in both measurements.

In the experiments under consideration, the unpolarized proton beam was scattered first by a target with known polarizing ability. The polarized beam obtained in this manner passed through a solenoid, which did not change the spin and momentum orientations, but turned the spin in the primary-scattering plane. A deflecting magnet then changed the relative orientation of the spin and the momentum to an angle $\pi/4$. The investigated scattering at the angle $\theta_l = 30^\circ$ from hydrogen was carried out in the same plane as the first scattering. Placed in front of a third scatterer, which played the role of an analyzer, was a second deflecting magnet, which changed the relative orientation of the final polarization and momentum in such a way that the polarization component of interest to us was perpendicular to the momentum.

It was found in this experiment that

$$P_A - P_B = 0.0019 \pm 0.009.$$

It is obvious from (26) and (19) that

$$P_A - P_B = \frac{8}{\sigma_0} \operatorname{Re} g^* t.$$

The value of the modulus of the T-invariant amplitude g was determined on the basis of the results of other experiments and equals $8\,|g| = 3.4\ (\text{mb/sr})^{1/2}$. The value obtained for σ_0 is 3.6 mb/sr. It follows therefore that

$$|t| \cos \alpha = 0.0020 \pm 0.010\ (\text{mb/sr})^{1/2},$$

where α is the phase difference between the amplitudes t and g. If it is assumed that $\cos \alpha \sim 1$, then $|t| \lesssim (1/2)\%\sigma_0$ (for one standard deviation). Using the results of the phase-shift analysis at 430 MeV energy, and assuming that the parameter λ_4 responsible for T-violation in the transitions ${}^3F_4 \rightleftarrows {}^3H_4$ vanishes, the authors of[17] reach the conclusion that $\lambda_2 \lesssim 0.06$ of the maximum value $\pi/2$. We see that the upper limit of λ_2 greatly exceeds the upper limit of $|t|$. This is connected with the smallness of the mixing parameter ϵ_2 at the energy under consideration. In connection with future experiments on T-invariance verification, we note that in pp scattering, in the entire energy region to ~600 MeV, the mixing parameters are small, making searches for possible T-violation in this region difficult. It may be sensible to set up analogous experiments on np scattering where, according to presently available phase-shift analysis results, the mixing parameter of the ${}^3S_1$ and ${}^3D_1$ states is $\epsilon_1 \sim 25^\circ$ at an energy of 310 MeV.

In addition, with further increase of the experimental accuracy, it will become necessary to take into account the bremsstrahlung effects, as was recently done by A. V. Tarasov (see[18]).

In the analysis of future experiments at high energies, where there are no detailed data on the N-N scattering amplitudes, it may be useful to employ the expressions derived in[18] for the ratio of the amplitude t in (17) to the other amplitudes in (16) directly in terms of measurable quantities.

II. VERIFICATION OF CPT INVARIANCE IN EXPERIMENTS OF THE SCATTERING OF ANTINUCLEONS BY NUCLEONS

In[19], attention was called to the unique possibilities of a direct verification of CPT invariance in the study of polarization effects in the process of elastic scattering of antiprotons by protons

$$\bar{p} + p \to \bar{p} + p. \tag{27}$$

The point is that CPT invariance imposes limitations on the antiproton-proton scattering matrix, and these lead to definite relations between the different polarization characteristics.

We denote by $M(\mathbf{p}', \mathbf{p})$ the matrix of the process (27), where $\mathbf{p}$ and $\mathbf{p}'$ are the momenta of the initial and final antiprotons. The invariance condition in CPT transformation is given by

$$M(\mathbf{p}', \mathbf{p}) = (U^{-1} P_\sigma M(-\mathbf{p}, -\mathbf{p}') P_\sigma U)^T, \tag{28}$$

where U is a matrix satisfying the conditions (4) and $P_\sigma = \frac{1}{2}(1 + \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$ is the operator of permutation of the spins of the nucleon and antinucleon (particle 1 will be taken to be the antinucleon). Using the invariance against rotations, we obtain in analogy with (6)

$$M(-\mathbf{p}, -\mathbf{p}') = (\boldsymbol{\sigma}_1 \mathbf{m})(\boldsymbol{\sigma}_2 \mathbf{m}) M(\mathbf{p}', \mathbf{p})(\boldsymbol{\sigma}_1 \mathbf{m})(\boldsymbol{\sigma}_2 \mathbf{m}). \tag{29}$$

From (28) and (29) follow relations between the different observable quantities. We present the simplest ones[20]:

$$P_1 = A_2, \quad P_2 = A_1, \tag{30}$$

where $P_i = (\mathbf{P}_i \cdot \mathbf{n})$ is the polarization of the i-th particle and $A_i = (\mathbf{A}_i \cdot \mathbf{n})$ is the asymmetry in the case when the initial particle i is polarized. A verification of these relations calls for experiments with polarized proton target and polarized antiprotons.

If CPT invariance is violated, then relations (30) do not hold. The amplitude which is not invariant against CPT transformation (assuming that P-parity is conserved) is given by

$$M'(\mathbf{p}', \mathbf{p}) = d(\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\mathbf{n} + e[(\boldsymbol{\sigma}_1 \mathbf{m})(\boldsymbol{\sigma}_2 \mathbf{l}) + (\boldsymbol{\sigma}_1 \mathbf{l})(\boldsymbol{\sigma}_2 \mathbf{m})]. \tag{31}$$

The first term in this expression is P- and T-invariant, but C-noninvariant, while the second term is P- and C-invariant but T-noninvariant. If CPT-invariance does not hold, then simultaneous measurement of all four observables contained in (30) will make it possible not only to establish the CPT violation, but also to ascertain[19] whether this violation is due to violation of C- or T-invariance.

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DISCUSSION

Ya. A. Smorodinskiĭ:

Assume that CPT-odd correlation is observed in an experiment with $\bar{p}p$ scattering. How does this change our picture of the world ?

V. N. Gribov:

In this experiment we verify whether the particle scattered by the proton is antiproton. For example, if we consider the scattering $\bar{\Lambda} + p \rightarrow \bar{\Lambda} + p$, then the amplitude, in the case of T conservation, contains six invariant functions, and differs thereby from the $\bar{p} + p \rightarrow \bar{p} + p$ amplitude, where there are only five functions.

Ya. A. Smorodinskiĭ:

If there was no real antiproton in the experiment, i.e., there is one other antiproton, already real, and the number of particles has doubled. This explains the experiment.

I. Yu. Kobzarev:

I wish to ask Gribov a question. Does he believe that if the proposed experiment shows that the forbidden term exists then this will denote, as proposed by Smorodinskiĭ, that there exists one other antiproton which is a true antiparticle relative to the proton?

V. N. Gribov:

From the point of view of theory - yes. Without a theory we cannot say anything.

K. Term-Martirosyan:

I wish to make a rather trivial remark. The question of verifying CPT invariance is radically different from verification of P or T invariance. In the latter, violation of invariance denotes the presence in the Lagrangian of "extra" terms (e.g., with an "extra" factor γ_5 in the case of P violation or with an additional phase factor $e^{i\delta}$ in the case of T violation), which can exist in principle. The task of the experiment is to determine whether these terms exist or not. In the case of CPT invariance the situation is entirely different. There is a well known Pauli-Luders theorem that there is no CPT violating local Lorentz-invariant interaction. It seems to me that none of us has ever seen such a Lagrangian in an any way reasonable form (I'm afraid that we shall never see it). It is therefore difficult to say that the experiment will verify the presence of some CPT-violating terms. It is clear that what is verified is something different, for example the fact referred to by Gribov, i.e., whether we deal with a particle and antiparticle or with two entirely different particles.

Ya. A. Smorodinskiĭ:

Ya. B. Zel'dovich asked to note two facts:

1. The discovery of CP-violation has clearly revealed charge asymmetry. In our world there are more K_{e3} decays with e^+ than with e^-. In the antiworld, an excess of e^- will be observed.

2. It is noted in the paper by Zel'dovich and Novikov (ZhETF Pis. Red. 6, 772 (1967) [JETP Lett. 6, 236 (1967)]) that the discovery of T-violation prevents the world from having the topology of a Moebius sheet. A world with a non-orientable metric admits of the possibility of a transition of a right-hand particle into a left-hand particle on going over a closed contour. If we add to this that the charge also changes in such a circuit, then in principle, a Moebius metric is possible in a CP-invariant world. The difference between the two charges becomes absolute only in a world with CP-violation.

I wish to add to this, on my own behalf, that in a world in which e^+ goes over into e^- (turning into a neutral particle somewhere along the way), this leads to electrodynamics without charge conservation. In such a world there would be no ordinary conservation laws at all, raising very great difficulties not noted in the paper of Zel'dovich and Novikov.

A. A. Grib:

CP-violation in K^0-meson decays is of great interest in connection with the question of the role of non-equivalent representations of commutation relations in quantum field theory. The K^0 meson is the only particle having charge (strangeness) that is conserved in certain phenomena (strong interactions) and not conserved in others (weak and superweak interactions), and has no other strictly conserved charges. This suggests therefore that if the K^0-meson in strong interactions that conserve strangeness and CP is described in terms of the Fock representation with vacuum $|\Phi_0\rangle$ (so that $\overline{K}^{0(-)}(\mathbf{p})|\Phi_0'\rangle = 0$, $K^{0(-)}(\mathbf{p})|\Phi_0\rangle = 0$), then the interaction that does not conserve strangeness and CP is obtained via a transition to another non-Fock representation of the commutation relations. In the latter case, there exists no vacuum for the operator $\overline{K}^{0(-)}(\mathbf{p})$, but there exists a vacuum $|\Phi_0'\rangle$ such that $a^{(-)}(\mathbf{p})|\Phi_0'\rangle = (\xi_p\overline{K}^{0(-)}(\mathbf{p}) + \eta_p K^{0(+)}(\mathbf{p}))|\Phi_0'\rangle = 0$, $\xi_p^2 - |\eta_p|^2 = 1$, $K^{0(-)}(\mathbf{p})|\Phi_0'\rangle = 0$.

An interaction of the type $g(\overline{K}^0K^0)^2$ in the Fock representation describes strong interactions of K^0 and $\overline{K}^0$ mesons, while in the new representation the appearance of "anomalous mean values"

$$\langle\Phi_0'|K^0K^0|\Phi_0'\rangle \text{and} \langle\Phi_0'|\overline{K}^0\overline{K}^0|\Phi_0'\rangle$$

leads to terms of the form $i\lambda\overline{K}^0\overline{K}^0 - i\lambda K^0K^0$, which correspond precisely to the Wolfenstein superweak interaction.

B. Pontecorvo:

What are the predictions of your model compared with the other models?

A. A. Grib:

The predictions of this model for K^0-meson decays coincide with the predictions of the Wolfenstein model. The purpose of the present discussion is to explain with which principle the very existence of the superweak interaction is connected. Unlike the Wolfenstein model, a recipe is presented here for obtaining superweak interaction. It is necessary to write the strong-interaction Lagrangian and to replace throughout the operator products K^0K^0 and $\overline{K}^0\overline{K}^0$ by the averages over the vacuum, identifying the products of the latter by the strong-interaction constant with the superweak-interaction constant. This procedure is perfectly analogous to the introduction of the spurion by Salam and Ward in ordinary weak interactions, when it is assumed that $\langle \Phi_0' | K^0 | \Phi_0' \rangle \neq 0$.

A. I. Vaĭnshteĭn:

It would seem that in such a spontaneous CP violation there should appear a massless particle. What can be said in this respect?

A. A. Grib:

This involves the so-called Goldstone theorem. The proof of this theorem is quite simple in theories with $\langle \Phi_0' | K^0 | \Phi_0' \rangle \neq 0$. In our case $\langle \Phi_0' | K^0K^0 | \Phi_0' \rangle \neq 0$, and to prove the theorem it is necessary to demonstrate the existence of "light-like" solutions of the Bethe-Salpeter equations, which is rather complicated problem. But even if the Goldstone particles do exist, we still do not know whether they take part in physical interactions. In a rigorous theory of representation of commutation relations (the Segal-Liu formalism), there exists no proof of this theorem. It seems to me that it is too early to speak of a physical meaning of this mathematically insufficiently clear theorem in the theory of elementary particles.

L. A. Khalfin:

It was indicated in a paper by L. I. Lapidus that a verification of a number of consequences of the unitarity relations, obtained from a phenomenological analysis of the K^0-$\overline{K}^0$ system, and in particular from the phase relations, may be a good test of CPT- and T-invariances. In the derivation of the unitarity relations, and consequently of all the conclusions from this derivation, only the most general premises of quantum theory were used, and, what is important, the assumption that the decays of the K_L and K_S states are strictly exponential. This assumption is equivalent to the statement that the mass distributions of the K_L and K_S mesons are described by simple poles. I wish to call attention to the fact that the unitarity relation and the consequences from it are exceedingly sensitive to this assumption. It is easy to show, for example, that if K_L and K_S mesons are described by poles of order higher than the first (Goldberger-Watson), then it follows automatically from the unitarity relation that

$$\langle L | S \rangle = 0,$$

regardless of whether CP-invariance is conserved or not. This result can be easily understood, since the decay law connected with the poles of order higher than the first causes the probability of the decay per unit time to depend on the time (inhomogeneity of the decay), and the decay probability at t = 0 is equal to zero. If it is assumed that*

$$\left.\begin{aligned} |K_L(t)\rangle &= (1+\alpha t)\exp\{-iM_L t\}|L\rangle, \\ |K_S(t)\rangle &= (1+\beta t)\exp\{-iM_S t\}|S\rangle, \end{aligned}\right\}$$

then it can be shown that the unitarity relation goes over into

$$\langle L | S \rangle [i(M_S - M_L^*) - \alpha - \beta] = \sum_F (F | T | L)^* (F | T | S).$$

It follows from the foregoing that great interest attaches to a thorough experimental determination of the detailed form of the laws of the decays of K_L and K_S meson in as large a time interval as possible and with as high an accuracy as possible. This is all the more interesting since, as we have seen, there are no reasonable and conceivable models of CPT violations, and therefore there are no theoretical predictions of the magnitudes of the effects connected with the possible CPT-violation. At the same time, the non-exponentiality assumption leads to concrete estimates of the expected effects for the experimental data. A careful measurement of the laws of the K_L and K_S mesons is necessary also in order to verify the model wherein the $K_0 \to 2\pi$ decay problem is explained as being due to the "mass filter," a model proposed by me recently (ZhETF Pis. Red. 3, 129 (1967) [JETP Lett. 3, 81 (1967)]). As to the presently available experimental data on the verification of the exponentiality of the decay laws for K_L and K_S mesons, they are completely inadequate. The estimates contained in the table of N. N. Nikolaev were obtained by reducing the results of experiments which as a rule were not aimed at verifying the exponential decay, and special experiments (in another time interval) with good statistics are necessary.

My second remark concerns the questions discussed in the paper by V. Ya. Faĭnberg. It was indicated in it that the application of the CPT theorem to unstable particles entails fundamental difficulties. This is obvious at least from the fact that for unstable particles there are no in- and out-states, without which the formulation of the CPT theorem is impossible. V. Ya. Faĭnberg has indicated that it is possible to speak of the applicability of the CPT theorem to unstable particles only if they are described exactly by simple poles, more accurately if there is no dependence of the properties of the unstable particles on the preparation. V. Ya. Faĭnberg has emphasized that this is valid with accuracy up to Γ/m. In my recent paper "On the Conditions of Admissible Distributions of Nonstable-particle Masses," Dokl. Akad Nauk SSSR (and a preprint) it is shown that if two unstable particles are produced simultaneously, then in the case of the K^0 meson, for example, when the K_L and K_S mass distributions strongly overlap, and the assumed independence of the preparation is valid only accurate to terms of order Γ_L/Γ_S.

*$\alpha \leqslant \Gamma_{L/2}$, $\beta < \Gamma_{S/2}$, otherwise the law of K_L and K_S meson decay would be nonmonotonic.

V. N. Gribov:

Why is it that only in the case of K^0 mesons is it meaningful to consider second-order poles? And why not verify for molecules or nuclei? What bearing does all this have on CPT?

L. A. Khalfin:

The effects I spoke about, namely the possible existence of higher-order poles and the dynamic "mass filter," are general and pertain, of course, not to K^0 mesons alone. What makes K^0 mesons unique among all elementary particles is the K_L, K_S structure with strong overlap with the mass distributions. Incidentally, verification for atoms, molecules, and nuclei entails its own rather significant experimental difficulties. As to CPT, let us assume that the experiments referred to by L. I. Lapidus have been performed and deviations from the predictions of CPT-invariance have been observed. Is this proof of CPT violation? Obviously not, since these deviations may be due to the non-exponential decays of the K_L and K_S states. This possibility (which is much less uncertain than the violation of CPT), cannot be "closed" a priori.

Ya. A. Smorodinskiĭ:

Did I correctly understand you to say that observation of deviations from CPT predictions is due to non-exponentiality?

L. A. Khalfin:

I would state more exactly that if such deviations are observed, they can be attributed to non-exponentiality.

F. L. Shapiro:

What about interference experiments in your model?

L. A. Khalfin:

Obviously, we are dealing here with two questions: the model with poles of higher orders, and my model with "mass filter." As to the model with higher-order poles, their influence on the interference experiments was considered in my paper (Dokl. Akad. Nauk SSSR **172**, 1059 (1967) [Sov. Phys.-Dokl. **12**, 143 (1967)], where all the required formulas are given, and the calculation of the phase shifts $\eta_{+-}(\eta_{00})$ in the superweak interaction model with higher-order poles can be readily performed. I shall not stop to discuss this in detail. As to my model with the "mass filter," all the conclusions of my model coincide effectively, i.e., for all ordinary experiments, as already mentioned, with the conclusions of the Wolfenstein model. The same pertains to the interference experiments. In this connection I wish to recall once more that the gist of my solution of the $K^0 \to 2\pi$ decay is that the decay of K_S, as a result of the "mass filter," consists not only of its regular exponential, but also another exponential with the time of the associatively created K_L meson. My model contains no interactions that transform K_L in K_S and vice-versa. Let us express the main result in terms of formulas. Let

$$m_1 + m_2 \longrightarrow m + M \longrightarrow m_4 + m_5 + m_6 + m_7.$$

Then, it follows from the rigorous energy-momentum conservation law "from the stable particles to the stable ones" that the mass distributions $\omega(m)$ and $W(M)$ cannot be arbitrary. Namely, let G be a closed region (Dalitz plot) of the (m, M) plane; the mass distributions $\omega(m)$ and $W(M)$ are mutually admissible if and only if for any measurable breakdowns A and B of the (m, M) plane, such that $A \times B \cap G = 0$ (empty set), the following equation is valid:

$$\int_A \omega(m)\, dm + \int_B W(M)\, dM \leqslant 1.$$

This indeed explains the influence of the mass distribution of one particle on the mass distribution of the other associatively produced particle, and leads to a dynamic "mass filter," which is essential in my model of solving the $K^0 \to 2\pi$ problem.

M. Veltman:

There is little reason for hoping that an accuracy better than 1% can be reached in $\bar{p}p$ annihilation, inasmuch as small effects of the type of polarization of $\bar{p}$ can become appreciable. The only thing that one can hope for is that in certain channels, for accidental reasons, there is a sufficiently large asymmetry. From the form of the histogram of the $\bar{p}p$ annihilation at rest it follows that the only candidate (to be sure, doubtful) is apparently the channel $\bar{p}p \to \pi^+\pi^-\pi^0$, in which, within definite regions of the Dalitz plot, there is an asymmetry equal to two standard errors (private communication from the CERN $\bar{p}p$ group).

L. B. Okun':

What is the connection between the polarization of the proton and charge asymmetry?

M. Veltman:

In C-reflection, $\bar{p}$ and p must interchange places, and if only one of them is polarized, then asymmetry can arise.

L. B. Okun':

Has the accuracy in the measurement of $g(\mu^+) - g(\mu^-)$ actually been increased by a factor of 15?

R. Finocchiaro:

Yes, actually.

Translated by J. G. Adashko