On the Possibility of Experimental Observation of Mirror Particles

I. Yu. Kobzarev, L. B. Okun' and I. Ya. Pomeranchuk

Institute for Theoretical and Experimental Physics, State Atomic Energy Commission

Submitted to JNP editor December 29, 1965

J. Nucl. Phys. (U.S.S.R.) **3**, 1154–1160 (June, 1966)

In connection with the discovery of *CP* violation in the decay $K_2^0 \to 2\pi$ the possibility is discussed, that "mirror" (*R*) particles exist in addition to the ordinary (*L*) particles. The introduction of these latter particles reestablishes the equivalence of left and right. It is shown that mirror particles cannot interact with ordinary particles strongly, semistrongly, or electromagnetically. Weak interactions between *L* and *R* particles are possible, owing to the exchange of neutrinos. *L* and *R* particles must have the same gravitational interaction. The possibility of existence and detection of macroscopic bodies (stars) made up of *R*-matter is discussed.

1. MIRROR PARTICLES AND *CPA* INVARIANCE

At the present time it is doubtless that the decay $K_2^0 \to 2\pi$ has indeed been observed in the experiments[1–4] and that *CP*-invariance is violated. This means that the equivalence of right and left does not exist in the world of observed particles.

In distinction from noninvariance under the proper Lorentz group, *CP* noninvariance does not lead to real theoretical difficulties. Indeed, a Lagrangian with complex constants leads to a *CP*-noninvariant but unitary, analytic, and *CPT*-invariant *S*-matrix. The problem of understanding how nature has made its choice among the "right-handed" and "left-handed" versions remains a task for a future theory.

It should be stressed that in a *CP*-noninvariant theory a pure mirror-reflection (without time reversal) does not map a physical process into another physical process. Such a mapping is realized only by a *CPT* transformation. Thus a reflection of the space axes must be accompanied by a reflection of the time axis. In this sense the space and time coordinates are not independent. This is a qualitatively new situation. Until now physicists believed that the "universe" Lagrangian, describing elementary particles, is invariant under all the transformations which leave the Lorentz interval $t^2 - \mathbf{x}^2$ invariant. This credo was not shaken by the discovery of *P*-noninvariance in 1956, since the hypothesis of conservation of combined invariance proposed by Landau[5] gave the possibility of considering the *CP* transformation as the physical realization of space reflection. The *T*-transformation remained an independent operation having the usual interpretation.

If one tries to preserve the independence of *P*- and *T*-reflections in the presence of *CP*-violation, and thus, to preserve the symmetry of nature with respect to left and right, one must assume that in addition to our world there exists a mirror-image world and that the elementary particles are doubled. In connection with the nonconservation of *P* in weak interactions, the possibility of existence of a mirror-world had been considered by Lee and Yang.[6] They assumed that in addition to the known particles, which they called left-handed (*L*), there exist also right-handed (*R*) particles. According to the ideas of [6], the operation of mirror reflection contains, in addition to a *CP*-transformation, the operation $L \rightleftarrows R$, which we denote here by *A*.[1)] The physical inversion is described by the operation *CPA*, and it is assumed that the total Lagrangian is invariant with respect to this operation.

As an example, we write down a *CPA*-invariant Lagrangian, describing the decays $\Lambda \to p\pi^-$, with the assumption that *CP* is violated in the usual weak interaction:

$$\mathscr{L} = \bar{p}_L(\alpha + \beta\gamma_5)\Lambda_L\varphi_{\pi L}^* + \bar{p}_L^C(\alpha^* - \beta^*\gamma_5)\Lambda_L^C\varphi_{\pi L} + \bar{p}_R^C(\alpha - \beta\gamma_5)\Lambda_R^C\varphi_{\pi L} + \bar{p}_R(\alpha^* + \beta^*\gamma_5)\Lambda_R\varphi_{\pi R}^*. \quad (1)$$

Here $\Lambda_L^C = \gamma_2\gamma_4\bar{\Lambda}_L$ and similarly for p_L^C, Λ_R^C, and p_R^C. The terms involving Λ_L^C and Λ_R^C are hermitian conjugates of the terms with Λ_L and Λ_R. The first two terms describe the decays of "our" particles and antiparticles: $\Lambda_L \to p_L\pi^-{}_L$ and $\bar{\Lambda}_L \to \bar{p}_L\pi^+{}_L$. The asymmetries in the decays $\Lambda_L \to p_L\pi^-{}_L$ and $\bar{\Lambda}_R \to \bar{p}_R\pi^+{}_R$ are equal in magnitude, but have opposite signs.[2)]

For a model in which *CP*-invariance is violated in the superweak interaction with $|\Delta S| = 2$,[7] a *CPA*-invariant Lagrangian for the transition $K_2 \to K_1$ has, apart from a factor, the form

$$\mathscr{L} = i(K_1^L K_2^L - K_1^R K_2^R). \quad (3)$$

Accordingly, in the case of a *C*-noninvariant but *p*-invariant electrodynamics[8,9] the effective Lagrangian

[1)]To be more precise, the *PA* transformation was considered in [6] rather than the *CPA* transformation.

[2)]Instead of *CPA*-invariance one could consider *PA*-invariance only. In this case the appropriate Lagrangian has the form

$$L = \bar{p}_L(\alpha + \beta\gamma_5)\Lambda_L\varphi^*{}_{\pi L} + \bar{p}_L{}^C(\alpha^* - \beta^*\gamma_5)\Lambda_L{}^C\varphi_{\pi L} + \bar{p}_R(\alpha - \beta\gamma_5)\Lambda_R\varphi^*{}_{\pi R} + \bar{p}_R{}^C(\alpha^* + \beta^*\gamma_5)\Lambda^C{}_R\varphi_{\pi R}. \quad (2)$$

For concreteness we shall discuss the case of *CPA*-invariance.

corresponding to $\pi^0 \to 2\gamma$ and $\pi^0 \to 3\gamma$ decays can be written symbolically as

$$L_{2\gamma} \sim e^2(\pi_L{}^0 2\gamma + \pi_R{}^0 2\gamma), \tag{4}$$
$$L_{3\gamma} \sim e^3(\pi_L{}^0 3\gamma - \pi_R{}^0 3\gamma), \tag{5}$$

with $L_{3\gamma}$ odd under *CP*.

2. THE INTERACTION BETWEEN *L* AND *R* PARTICLES

The main purpose of this paper is to consider the possible types of interactions between ordinary particles (*L*) and the mirror particles (*R*).

In Lee and Yang's work,[6] the possibility of electromagnetic or even strong interactions of *L* and *R* particles was admitted. We shall show below that in reality this is incompatible with the experimental data. The existing experimental data exclude even the possibility of semistrong interactions.

In distinction from photons, neutrinos *can* belong to both worlds and the gravitons *must* be common to both, if we wish the introduction of the *R*-world to have any physical meaning at all.

3. ELECTROMAGNETIC INTERACTIONS. COMMON PHOTONS (?)

We start with the case of a common electromagnetic interaction for the two kinds of particles. In this theory there should exist two kinds of π^0 mesons $\pi_L{}^0$ and $\pi_R{}^0$ ($\pi_R{}^0 = -CPA\pi_L{}^0$). In the presence of a common photon, the following transition is possible

$$\pi_R{}^0 \rightleftarrows 2\gamma \rightleftarrows \pi_L{}^0.$$

This will give rise to two states

$$\pi_1{}^0 = \frac{1}{\sqrt{2}}(\pi_R{}^0 - \pi_L{}^0), \qquad \pi_2{}^0 = \frac{1}{\sqrt{2}}(\pi_R{}^0 + \pi_L{}^0),$$

where $\pi_1{}^0$ is even under *CPA* (odd under *CA*) and $\pi_2{}^0$ is odd under *CPA* (even under *CA*). We shall assume that the electromagnetic interaction is even under *CPA* and *P*, and thus also under *CA*, but is not necessarily even under *C*.[8,9] By assumption, a γ-(photon) transforms into itself under *CA*. Then the $\pi_1{}^0$ state, which has odd *CA*, cannot decay into two photons, real or virtual, but can decay into three photons. Since the width of such a decay is small, this $\pi_1{}^0$ meson would be long-lived, in contradiction with experiments. Thus, for example, in the charge exchange reaction $\pi^- \to \pi^0$, part of the generated π^0 mesons would not decay into two photons. The same is true for π^0 mesons which appear in the decay of the Λ^0 hyperon or of K^0 mesons in the reaction $\pi^- p \to \Lambda^0 K^0$.

This conclusion remains valid if in addition to the common electromagnetic interaction of the *R* and *L* particles, there exists also a common strong interaction.

Thus, there should exist photons of two types: γ_L and γ_R. It follows that the particles which are common to both worlds must necessarily be neutral. Otherwise we would have separate violations of the conservation laws of electric *L* and *R* currents. Such particles could in principle be neutral isoscalar mesons, the neutrinos, the schizons W^0 and $\overline{W}{}^0$,[10] the gravitons and other yet unknown neutral particles.

4. THE STRONG INTERACTION. COMMON MESONS (?)

We now consider the case when there are two photons, γ_L and γ_R, and the only common interaction of the *L* and *R* particles is the strong interaction. In this case there would exist two π^0 mesons with approximately equal lifetimes, which is in itself not in contradiction with experiment. These pions will decay into $\gamma_L\gamma_L$, $\gamma_R\gamma_R$, and $\gamma_L\gamma_R$. The strong interaction between *L* and *R* particles must be isospin-invariant. Therefore, the mixing of $\pi_L{}^0$ and $\pi_R{}^0$ (both having $T = 1$) will involve virtual photons and will be of electromagnetic order of smallness (order α^2, cf. Fig. 1). During the lifetime of the π^0 meson, a partial mixing of $\pi_L{}^0$ and $\pi_R{}^0$ will occur. Thus, the experimentally observed π^0 mesons should emit γ_R photons in a certain fraction of the events. If one takes into account that the doubling of photons also involves the doubling of the leptons (otherwise the usual relation between *ee* and *ep* cross sections would be violated), the observed decay probability for $\pi^0 \to \gamma e^+ e^-$ would be smaller than the usual one (for which the experiments agree with the standard theory): the γ_R photons would convert into invisible *R* leptons. Unfortunately we are not in a position to estimate the degree of $\pi_L{}^0 \leftrightarrow \pi_R{}^0$ mixing and therefore have to consider other arguments which exclude a common strong interaction for the *L* and *R* particles.

Generally speaking, the existence of a common strong interaction between the *L* and *R* worlds would lead to essential modifications of the properties of strong interactions. In pair production processes along with usual pairs $N_L\overline{N}_L$ (N = nucleon) there would also appear pairs $N_R\overline{N}_R$. The fate of such *R* antiparticles would depend on whether bound mesonic states of the type $\overline{N}_R N_L$ are possible. Should such states be possible, they would be stable, since there are no transitions between *L* and *R* nucleons even in weak interactions. (If the converse were true anomalous nuclei would appear in beta decay, involving *R* nucleons.) The experiments

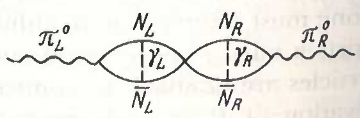

Fig. 1.

of [11-14] indicate that there are no charged stable particles in nature which are lighter than the deuteron (except, of course, the proton and electron). If bound states of the type $\bar{N}_R N_L$ were forbidden, the R antinucleon would not annihilate in ordinary matter. Unfortunately the data on antiproton annihilation obtained in [15] have no relation to this problem, since the R antiprotons have no electric L charge, do not interact with L photons and do not leave ionization tracks.

The strong interactions between L and R particles would lead to a strong mixing of the L and R mesons ($\omega_L^0 \leftrightarrow \omega_R^0$, $\eta_L^0 \leftrightarrow \eta_R^0$ etc.). As a result A-even and A-odd states would be formed, which would decay with equal probabilities into visible L particles and invisible R particles (this relates in particular to η mesons, which would decay α^2 times slower than they would mix). We can conclude that the available experimental data are in contradiction with the hypothesis that there exists a strong interaction between the L and R particles.

As regards a semistrong interaction between L and R particles, it is excluded by the data obtained in the CERN neutrino experiment.[16] Indeed, the steel shield of 25 m thickness used in this experiment would have allowed a considerable number of π_R mesons to pass (10^6 particles), even if their cross section would be only one order of magnitude smaller than the nuclear. In the neutrino experiment, neutrinos have been registered which are generated with an intensity equal to that of the π mesons and interact 13–14 orders of magnitude weaker. Therefore, mirror particles, in particular π_R mesons, generated 10^6 times less frequent than ordinary particles, and being absorbed with a cross section 10^6 times smaller than the nuclear one ($\sim 10^{-32}$ cm^2), if they existed, should be efficiently registered in the CERN experiment. One can thus assert, that the interaction between L and R hadrons is excluded, as long as the interaction constant g^2 for this interaction satisfies the inequality $g^2 > 10^{-6}$.

5. THE WEAK INTERACTION. COMMON NEUTRINOS[3)]

None of the experiments done so far is in contradiction with the assumption that neutrinos are common for the L and R particles. The Lagrangian of the weak interactions has, for example, the form

$$\mathcal{L} = \frac{G}{\sqrt{2}} (j_L^+ j_L + j_R^+ j_R), \qquad (6)$$

where

$$j_L = \bar{\nu}_e O_L e_L + \bar{\nu}_\mu O_L \mu_L + \cos\theta\, \bar{p}_L O_L n_L$$
$$+ \sin\theta\, \bar{p}_L O_L \lambda_L,$$

[3)]The question of the place of neutrinos in the present parity doubling scheme was posed to us by B. M. Pontecorvo.

$$j_R = \bar{\nu}_e O_R e_R + \bar{\nu}_\mu O_R \mu_R + \cos\theta\, \bar{p}_R O_R n_R$$
$$+ \sin\theta\, \bar{p}_R O_R \lambda_R. \qquad (7)$$

In the $V-A$ theory $O_R = O_L = \gamma_\alpha(1+\gamma_5)$. In the general case $O_R = (CP)^{-1} O_L (CP)$. Such a Lagrangian corresponds to the fact, that if the W bosons exist, there should be two types: W_L and W_R. Unfortunately, experiments on the conversion of neutrinos into R particles do not seem realizable. For example, the generation of R particles in a neutrino reaction like the one described by Fig. 2 could be observed only through the recoil proton with kinematics which disagrees with elastic νp scattering. One should take into account that for such experiments it is necessary to know the neutrino momentum and one has to be able to exclude cases when the recoil proton emits a bremsstrahlung photon.

Neutrino astronomy could yeild unexpected results in connection with the properties of the neutrino under discussion. If a bright R object would be situated in the neighborhood of our solar system, and this object would emit, like the sun, a flux of neutrinos, one could not observe the object either via its photons (γ_R) or its corpuscular radiation (e_R,p_R) but it might be a bright object on our "neutrino firmament."

6. THE WEAK INTERACTION. COMMON W^0 BOSONS (?)

The existence of common W^0 bosons with a universal interaction constant for interactions with L and R particles is excluded by experiment, since an unobservable π_R^0-meson would be generated in this case in hyperon and K-meson decays in addition to π_L^0 mesons, and unobservable $\pi_R^+\pi_R^-$ pairs in place of $\pi_L^+\pi_L^-$ pairs.

7. THE GRAVITATIONAL INTERACTION. COMMON GRAVITONS

If R-matter exists it should interact with L-matter via gravitation. If R-matter has any other interaction with ordinary matter, the gravitational interaction must contain the total matter tensor of L-matter and R-matter with a common constant G. Otherwise, the interaction between ordinary matter and R-matter with a non-conserved matter tensor for ordinary matter, would lead to contradictions in the gravitational

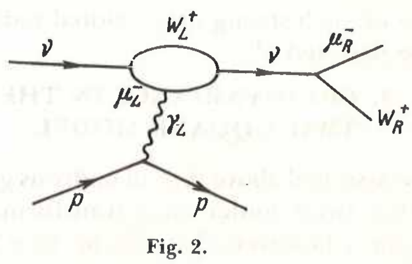

Fig. 2.

equations. It would seem at first sight, that if the graviton is the only particle common to the two worlds, different constants G_L and G_R would be possible. In particular, it would be conceivable that the graviton has vanishing interaction with R-matter. It is however obvious that if $G_R = 0$ and there are no other interactions between R- and L-matter, the assertion that R-matter exists becomes devoid of any physical significance. If $G_R \neq G_L \neq 0$, there appear difficulties in connection with the fact that the "total gravitational charge" of a closed system possessing kinetic energy would vary as this energy goes over from L-matter to R-matter components. Such a nonconservation of gravitational charge should lead to the appearance of a mass for the graviton, and consequently to a finite range for the gravitational interaction, on the basis of arguments similar to those advanced by Lyuboshitz, Okonov, and Podgoretskiĭ[17] in order to exclude the existence of long-range forces associated with hypercharge. If R-matter would interact with our world only via gravitational interactions, it should exhibit very peculiar properties. For example, R-matter could form absolutely invisible and absolutely penetrable (by ordinary matter) macroscopic bodies. The passing of such an object, with a mass of the order of planetary mass, through the solar system would manifest itself only through perturbations of the planetary orbits, which would be strong in close encounters. A certain amount of R-matter could exist inside the central regions of the sun or the planets, moving along with these objects, and would manifest itself only by the fact that the mass determined in gravitational effects is larger than their "physical" mass. Such a situation would be extremely artificial. Any R-matter which would have been captured by the gravitational field of the earth at its formation should have some momentum relative to the center of mass of the L-earth + R-earth. Thus the L-earth and R-earth would be in oscillation relative to their common center of mass. If the R-earth had an appreciable mass such oscillations should manifest themselves. Even if at some time the amplitude of such oscillations would vanish, oscillations should appear, as remarked by Frank-Kamenetskiĭ, due to meteoric bombardment. Thus the presence of large quantities of R-matter in our solar system is very unlikely.

We note that if a double star made of R-matter would be situated near our solar system, it could be the source of such strong gravitational radiation, that it could be detected.[18]

8. *CPA*-INVARIANCE IN THE TWO-Λ-QUARK MODEL

We have assumed above that all hadrons go over into their mirror twins under an A-transformation. One could require, however, that this be true not for all hadrons, but only for some of them. Such a requirement is satisfied by the composite model proposed by Vladimirskiĭ[19] in which there are two Λ-quarks (Λ_a and Λ_b) with identical strong interactions. In this model the A-transformation interchanges Λ_a with Λ_b. According to [19] A-invariance is violated by an interaction which is weaker than electromagnetic, therefore the corresponding "isogroup" $SU_2(\Lambda_a,\Lambda_b)$ is a more accurate group than the usual isospin group $SU_2(p,n)$. We shall show that the requirement of CPA-invariance leads in this model to a contradiction with experiments on neutral K mesons. In the two-Λ-quark model there are four neutral K mesons: K_1^a, K_1^b, K_2^a and K_2^b, which transform into each other. There are two diagonal states with positive CPA-parity, E_1 and E_2, and two states with negative CPA-parity, O_1 and O_2. The first are linear superpositions of the states $K_1^a + K_1^b$ and $K_2^a - K_2^b$, and the second are superpositions of $K_1^a - K_1^b$ and $K_2^a + K_2^b$. A $\pi^+\pi^-$ system in an S-state is CPA-even, therefore decays into such a system can come only from CPA-even mesons E_1 and E_2. If the lifetimes of E_1 and E_2 are comparable ($\tau_{E_1} \sim \tau_{E_2} \sim 10^{-10}$ sec) one cannot explain the outcome of the experiments of Christenson et al.[1-3] If one assumes that $\tau_{E_1} \sim 10^{-10}$ sec and $\tau_{E_2} \sim 10^{-8}$ sec, one can perhaps explain these experiments, but in this case, during a time of the order 10^{-10} sec, only 1/6, and not 1/3, of all K^0 mesons generated in a reaction would decay into $\pi^+\pi^-$. This conclusion is in disagreement with experiments on associated production of K^0 mesons ($\pi^-p \to \Lambda^0K^0$)[20] and charge exchange ($K^+n \to K^0p$).[21]

9. CONCLUSION

The consideration of the available experimental data leads us to the following conclusions.

1. If they exist at all, mirror particles interact with our particles in a relatively weak manner.

2. Within the limits of the solar system there are considerably fewer mirror particles than ordinary particles.

Both these conclusions do not imply that mirror particles do not exist at all, or that if they exist, they are absent from the solar system in general or the interior of the earth, in particular.

3. If stars made up of R-matter exist in the neighborhood of the solar system, such stars would not be detectable by ordinary methods, but could be detected via their neutrino or gravitational radiations.

The main result of the present paper, consisting in the conclusion of the possibility of only a very weak interaction between mirror matter and ordinary matter, and that the upper bound for the concentration of mirror-matter in the solar system is small, does not add to the attractiveness of the hypothesis of the existence of mirror matter.

The authors are grateful to V. N. Gribov, V. I. Kogan, S. B. Pikel'ner, B. M. Pontecorvo, D. A. Frank-Kamenetskiĭ, and I. S. Shapiro for interesting discussions.

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, *Phys. Rev. Lett.* **13**, 138 (1964).

[2] X. de Bouard, D. Dekkers, B. Gordan, R. Mermod, T. R. Willits, K. Winter, P. Scharff, L. Valentin, M. Vivavgent, and M. Bott-Bodenhausen, *Phys. Lett.* **15**, 58 (1965).

[3] W. Galbraith, G. Manning, A. E. Taylor, B. D. Jones, and J. Males, *Phys. Rev. Lett.* **14**, 383 (1965).

[4] V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon, *Phys. Rev. Lett.* **15**, 73 (1965).

[5] L. D. Landau, *JETP* **32**, 405 (1957), *Soviet Phys. JETP* **5**, 336 (1957).

[6] T. D. Lee and C. N. Yang, *Phys. Rev.* **104**, 254 (1956).

[7] L. Wolfenstein, *Phys. Rev. Lett.* **13**, 562 (1964).

[8] J. Bernstein, G. Feinberg, and T. D. Lee, *Phys. Rev.* **139**, B 1650 (1965).

[9] S. Barshay, *Phys. Lett.* **17**, 78 (1965).

[10] T. D. Lee and C. N. Yang, *Phys. Rev.* **119**, 1410 (1960).

[11] L. Gilly, B. Leontic, A. Lundby, R. Meunier, J. P. Stroot, and M. Szeptycka, *Proc. Rochester Conf. 1960*, p. 808.

[12] G. von Dardel, R. M. Mermod, G. Weber, and R. Winter, *Proc. Rochester Conf. 1960*, p. 836.

[13] V. T. Cocconi, T. Fazzini, G. Fidecaro, M. Legros, N. H. Lipman, and A. W. Merrison, *Phys. Rev. Lett.* **5**, 19 (1960).

[14] D. E. Dorfman, J. Eades, L. M. Lederman, W. Lee, and C. C. Ting, *Phys. Rev. Lett.* **14**, 1003 (1965).

[15] E. Amaldi, G. Baroni, G. Belletini, C. Castagnoli, M. Ferro-Luzzi, and A. Manfredini, *Nuovo cimento* **14**, 977 (1959).

[16] G. Bernardini, *Proc. of the Conf. on High Energy Physics*, Dubna, 1964.

[17] V. L. Lyuboshitz, É. O. Okonov, and M. I. Podgoretskiĭ, *YaF* **1**, 490 (1965), *Soviet JNP* **1**, 349 (1965).

[18] V. B. Braginskiĭ, *UFN* **86**, 433 (1965), *Soviet Phys. Uspekhi* **8**, 513 (1966).

[19] V. V. Vladimirskiĭ, *YaF* **2**, 1087 (1965), *J. Nucl. Phys.* **2**, 776 (1966).

[20] D. A. Glaser, *Proc. of 1958 Conf. on High Energy Physics at CERN*, p. 273.

[21] J. L. Brown, J. A. Kadyk, G. H. Trilling, B. R. Roe, D. Sinclair, and J. C. Van der Velde, *Phys. Rev.* **130**, 769 (1963).

Translated by M. E. Mayer