

About New Space-Time Symmetries in Relativity and Quantum Mechanics.

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Summary. — Some consequences of the space-time symmetries previously studied within extended relativity are exploited, and that study is improved. In particular, it is shown that relativity requires antiparticles to be formally associated with *negative* rest masses (but with *positive* relativistic masses and energies, of course!). The physical and geometrical meaning of *chirality* P_5 is derived, in such a context, and shown to be essentially connected with the inversion of a *fifth* axis (axis related to the rest-mass). In *five dimensions*, from the frame with all the (five) axes inverted, an observer would *e.g.* describe *antimatter* exactly so as the initial (noninverted) observer would describe *matter*, and *vice versa*. By applying what precedes to relativistic quantum mechanics (*e.g.* to fermion fields and Dirac equations), we get—among other things—a « *strong \overline{CPT} theorem* » (see the text): « Under inversion of all five axes x, y, z, t, m_0 , not only physical laws (of mechanics and electromagnetism, at least) are covariant, but even physical fields are invariant ».

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1. – Introduction.

Recently, special relativity has been suitably *generalized* ⁽¹⁾ on the basis of the three postulates ⁽¹⁾:

1) *principle of relativity* (without any *a priori* restriction on the inertial-frame relative speed),

2) space-time homogeneity and space isotropy,

3) *principle of retarded causality* (equivalent to the Dirac-Stückelberg-Feynman-Sudarshan «reinterpretation principle») ^(*).

All the postulates above are *compatible* ⁽¹⁾, and are enough for deriving not only usual relativity but also the «extended relativity» ⁽¹⁾. It is not necessary to assume light speed invariance, since from postulates 1) and 2) the existence of an invariant speed directly follows ⁽¹⁾.

The *first two postulates* (without the explicit, spurious assumption $|v| < c$) allow one to derive ⁽¹⁾ the «generalized Lorentz transformations» (GLT). They form a new group G , whose elements are now *all possible rotations in space-time*. All the elements L of G are «proper» transformations (*i.e.* unimodular, with $\det L = +1$). In particular the total inversion -1 is a particular GLT:

$$(1) \quad -1 \in G.$$

Incidentally, let us observe that the total inversion (which was considered as a discrete operation) has been obtained through a rotation by a «continuously» varying angle ⁽²⁾. This is analogous—in the Euclidean case—to the fact that two mirror images, lying on a plane (and that within plane geometry can be taken into each other *only* by a discrete operation), when passing to 3-dimensional geometry can be brought and superposed onto each other through a continuous rotation in *space*.

The *third postulate* («RIP») is necessary—and sufficient, both for bradyons ⁽³⁾ and tachyons—to avoid information transmission into the past. The «RIP» allowed us ⁽¹⁾—thus receiving a quite positive confirmation—to predict and explain the existence of *antiparticles*, exactly with all their properties as verified by experience ^(1,4).

⁽¹⁾ E. RECAMI and R. MIGNANI: *Riv. Nuovo Cimento*, **4**, 209, 398 (1974), and references therein.

^(*) This «third postulate» can be shown to be equivalent ⁽¹⁾ to the assumption that «negative-energy particles travelling forward in time do not exist».

⁽²⁾ E. RECAMI and R. MIGNANI: *Riv. Nuovo Cimento*, **4**, 209 (1974), p. 227.

⁽³⁾ Usual ($v^2 < c^2$) particles. See *e.g.* ref. ⁽¹⁾. In the following, when convenient, we shall use units such that *numerically* $c = 1$.

⁽⁴⁾ R. MIGNANI and E. RECAMI: *Lett. Nuovo Cimento*, **11**, 421 (1974); *Nuovo Cimento*, **24 A**, 438 (1974); *Int. Journ. Theor. Phys.*, **12**, 299 (1975).

Moreover, the « reinterpretation principle » (« RIP ») was shown ^(1,4) to be *necessary* to the self-consistency ^(5,6) of special relativity and of extended relativity: for instance, the *generalized* velocity composition law ⁽¹⁾ directly provides the velocities of the *reinterpreted* objects ⁽⁴⁾.

Let us also remember that the « strong reflection » $\bar{P}\bar{T}$ has been shown by us ⁽⁴⁾ to be equivalent to the usual *CPT* operation

$$(2) \quad -1 \equiv \bar{P}\bar{T} = CPT,$$

where in our formalism \bar{T} means the « strong » *T*-reversal (*i.e.* inversion of the fourth components of all four-vectors) ⁽⁴⁾, and practically ⁽⁴⁾ $\bar{P} \equiv P$. Obviously, the new group *G* will contain—besides the usual proper, orthochronous Lorentz transformations \mathcal{L} —also the nonorthochronous ones $-\mathcal{L}$:

$$(3) \quad -\mathcal{L} = -1 \mathcal{L} = \bar{P}\bar{T} \mathcal{L} = CPT \mathcal{L}.$$

Our present aims are to improve the search for symmetries already accomplished within relativity ⁽¹⁾, and to apply our results to quantum mechanics too.

2. – Negative rest masses (but positive relativistic masses!) must be attributed to antiparticles.

Our *first* aim is to make explicit a result that—although implicitly contained in our previous ⁽¹⁾ formalism—has not been put forth till now.

In fact, close inspection of fig. 16 in ref. ⁽¹⁾, here reported as fig. 1, shows that the « RIP » does change—among other things—the 3-momentum sign but does not affect the 3-velocity sign; *i.e.* it changes the rest-mass sign. Precisely, the « RIP » turns out to be equivalent to changing the sign of all the additive charges *and* of the rest mass (besides changing emission into absorption, and *vice versa*) ^(1,4):

$$(4) \quad \text{« RIP »} = CC_{m_0} X = \bar{C}X,$$

$$(5) \quad \bar{C} \equiv CC_{m_0},$$

⁽⁵⁾ Since we belong to the macrophysical world and therefore we « explore » the space-time going *forward in time*, then we cannot even « see » a particle go backwards in time ⁽¹⁾: we shall always see its « reinterpreted » ^(1,6) antiparticle, going forward in time. Therefore, the « RIP » not only *can* but even *must* be applied ⁽⁴⁾, as already assumed in ref. ⁽¹⁾.

⁽⁶⁾ See also E. RECAMI: *I tachioni*, in *Enciclopedia EST-Mondadori, Annuario 1973* (Milano, 1973), p. 85; *Scientia*, **109**, 721 (1974) and to appear; E. RECAMI and E. MODICA: *Lett. Nuovo Cimento*, **12**, 263 (1975); P. CALDIROLA and E. RECAMI: in *Proceedings of the Conference on the Concept of Time, Genova, 1976* (to appear); M. PAVŠIČ and E. RECAMI: submitted for publication.

where C is the conjugation of *all* additive charges, C_{m_0} is the rest-mass sign inversion and X operates the exchange absorption \rightleftharpoons emission. The quantity \bar{C} will be called « strong conjugation ».

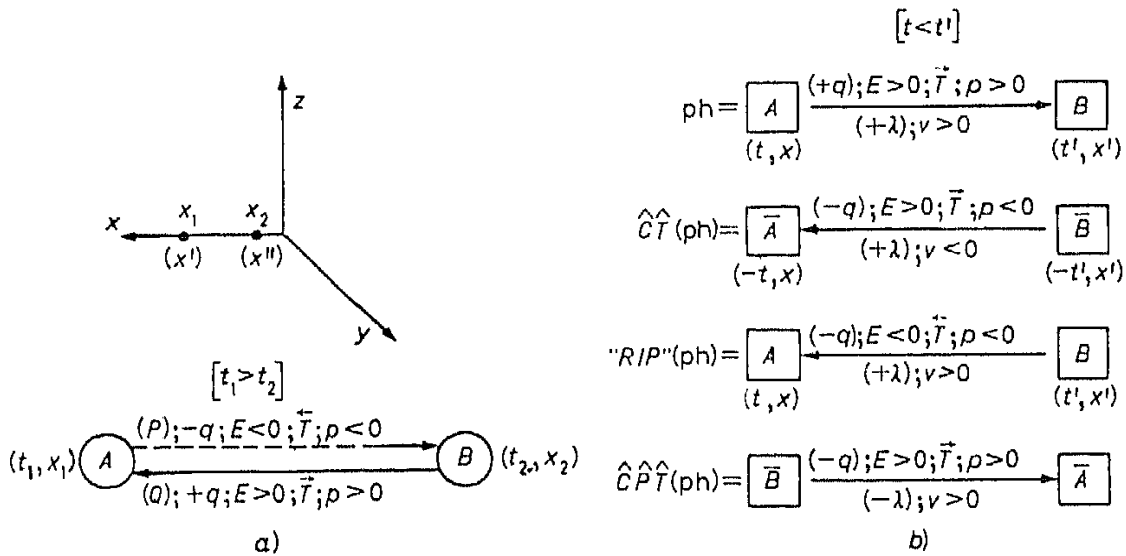


Fig. 1. - a) recalls that the exchange from A to B of a particle P with *negative* energy (and *e.g.* all negative « charges ») and travelling *backwards* in time can and *must* be reinterpreted as the exchange *from* B to A of a particle Q with *positive* energy (and positive « charges »), travelling *forward* in time. Particle Q may be shown to be the *antiparticle* of the initial particle (except for its helicity). See ref. (1) and the text. b) shows how a certain phenomenon ph is acted upon by some operations as CP , CPT and the « RIP » (reinterpretation procedure; cf. our third postulate).

In other words, let us clarify the following. Application of the operation $\overline{PT} \in G$ and of the third postulate « RIP » brings—merely within special relativity—from a particle to its antiparticle (1,4). Namely:

a) the « proper » operation (7) \overline{PT} acts as a particular space-time rotation, changing the signs of all four-vector components and leaving all scalars invariant (rest mass included);

b) the « RIP », on the contrary, does change the sign of the additive charges *and* of the rest mass.

As a result, *antiparticles must be attributed negative rest masses*, even if they maintain positive energy and positive relativistic mass (8)!

(7) In our framework, $CPT = \overline{PT}$ is a *linear* operator (as is any element of G) in the pseudo-Euclidean space.

(8) This necessity has been noticed—through different ways—by G. ZIINO: preprint (University of Palermo, 1975), to appear in *Lett. Nuovo Cimento*; and by J. E. EDMONDS jr.: preprint (Claremont Colleges, Cal., 1975), submitted to *Lett. Nuovo Cimento*; preprint (San Diego S. Univ., Cal., 1974), submitted to *Comm. Math. Phys.* See also P. WINTERBERG: *Lett. Nuovo Cimento*, **13**, 697 (1975).

For clarity's sake, let us notice the following. If u_0 is the time component of the 4-velocity, one has for any free particle, in covariant form,

$$(6) \quad E \equiv p_0 = m_0 u_0 c^2.$$

Now, any operation $-\mathcal{L}$ (e.g. the \overline{PT} operation) changes the sign—among other things—of all time components:

$$(7) \quad E' = -E = m_0(-u_0)c^2 = -m_0 u_0 c^2.$$

Afterwards, when applying the « RIP » so as to get the corresponding antiparticle, we have finally (for the antiparticle)

$$E'' = -E' = (-m_0)(-u_0)c^2,$$

so that the antiparticle (endowed of course with the 4-velocity component $-u_0$) remains with a *negative* rest mass. Notice explicitly that, from $E = m_0 u_0 c^2$, we have for objects at rest

$$(8) \quad \begin{cases} E = + m_0 c^2 & \text{for free particles } (m_0 > 0), \\ E = - m_0 c^2 & \text{for free antiparticles } (m_0 < 0), \end{cases}$$

so that

$$(9) \quad E = + |m_0|c^2$$

always holds, for all particles and antiparticles. Attention should however be paid to the fact that eqs. (8) do *not* violate covariance, since they *both* descend from the covariant expression (6); in particular, *the minus sign in the second of eqs. (8) comes from u_0* (which becomes ± 1 , in the rest limit, for particles and antiparticles respectively).

3. — Improving relativistic symmetries.

At this point let us *improve* Mignani and Recami's formalism for space-time symmetries in extended relativity^(1,4).

Let us re-derive the equivalence of our « strong reflection » \overline{PT} with the usual *CPT* operation. Since \overline{PT} means the sign inversion of all components of all four-vectors, for getting such an effect it is enough to write

$$(10) \quad \overline{PT} \equiv PT u_0 u_i X^{-1} \quad (i = 1, 2, 3),$$

where $X^{-1} \equiv X$ has been introduced because ordinary *T* contains the emis-

sion \rightleftharpoons absorption exchange X (differently from our \bar{T})⁽¹⁾. Now, by applying the « RIP » one immediately gets

$$(11) \quad \text{« RIP »}(\bar{P}\bar{T}) = \bar{C}X(PTu_0u_iX^{-1}) = CPT,$$

that is to say

$$\bar{P}\bar{T} \stackrel{\text{« RIP »}}{\equiv} CPT,$$

where C is the usual conjugation (or better the conjugation of all usual, *conserved* additive charges) and \bar{C} is defined in eq. (5). In fact, the 4-velocity inversion is equivalent to the rest-mass inversion: $u_0u_i = C_{m_0}$.

From eq. (11) it follows that (whenever the « RIP » is to be applied)

$$(12) \quad C \stackrel{\text{« RIP »}}{\equiv} C_{m_0}X,$$

i.e. the « charge » conjugation is merely equivalent (under the « RIP ») to the rest-mass inversion together with an absorption \rightleftharpoons emission exchange. For instance, under the action of C , the exchange of an electron from A to B becomes essentially the exchange of a positron from B to A ⁽¹⁾. Moreover,

$$\bar{C} \stackrel{\text{« RIP »}}{\equiv} X.$$

Before going to the next section, let us clarify also the following. The charge density $\varrho = \varrho_0u_0$ (the quantity ϱ_0 being the *invariant*, proper charge density) changes sign *e.g.* under the operation $\bar{P}\bar{T} \equiv CPT$; therefore the quantities

$$(13a) \quad q_1 \equiv \int \varrho |dV|$$

and

$$(13b) \quad q_2 \equiv \int \varrho \cdot dV$$

represent respectively the charge *after* and *before* the reinterpretation procedure⁽¹⁾. In ref. (1) we chose the case (13a).

4. - Geometrical interpretation of chirality and all that; and quantum mechanics.

Let us confine ourselves to the « world » of mechanics and electromagnetism, as usual in relativity. We already mentioned that, in ref. (9), from the fact that antiparticles must be attributed a negative rest mass, some interesting consequences have been put forth for *quantum mechanics*. Let us come closer

(9) G. ZIINO: *Lett. Nuovo Cimento*, **15**, 449 (1976).

to this point. By inspection of the free Dirac equation, the fact that only the condition $m_0(\text{fermion}) = -m_0(\text{antifermion})$ ensures opposite intrinsic parities for electrons and positons has been noticed in ref. (9). In this way the rest mass m_0 becomes a *fifth* co-ordinate besides the four-momentum ones (as already suggested also by one of the present authors (10)), in the sense that we have to invert also m_0 in order to go from the (Dirac) equation to the (Dirac) anti-equation. We shall come back to this point (11) in the following. From those observations, a new formal definition of \bar{C} has been derived (valid even in the nonfree case) (12):

$$(14) \quad \bar{C}^{-1} \psi \bar{C} = \gamma^5 \psi \equiv P_5^{-1} \psi P_5,$$

i.e. the chirality operation P_5 is recognized (in the case of states with definite parity) to be nothing but \bar{C} :

$$(14 \text{ bis}) \quad P_5 \equiv \bar{C} \equiv C C_{m_0};$$

thence (whenever the « RIP » is to be applied)

$$P_5 \stackrel{(\text{RIP})}{=} X.$$

Notice that, when dealing with nonfree fermions, the strong conjugation \bar{C} will operate both rest-mass and charge inversions; so that the chirality P_5 will act the same way. Moreover, since when going from Dirac equation to Dirac antiequation the charges are inverted strictly *together with* the rest mass, now the fifth axis can be considered—under this respect—as representing either rest mass or charges (13) (see the following). Notice also that, in relativistic quantum mechanics, when in the presence of electromagnetic interactions, the separate operators C and C_{m_0} do not lead to real states, since the real anti-particle—having both rest mass and charges inverted—is obtained only through \bar{C} .

(10) E. RECAMI and C. SPITALERI: *Scientia*, **110**, 205 (1975). See also ref. (11).

(11) P. CALDIROLA: *Nuovo Cimento*, **19**, 25 (1942); *Suppl. Nuovo Cimento*, **3**, 297 (1956); A. MADUEMEZIA: internal report IC/68/78 (ICTP, Trieste, 1968); J. D. EDMONDS jr.: preprint (S. Diego S. Univ., Cal., 1974), to appear in *Found. Phys.*; preprint (S. Diego S. Univ., Cal., 1974), to appear in *Int. Journ. Theor. Phys.*; I. GOLDMAN and N. ROSEN: *Gen. Rel. Grav.*, **2**, 267 (1971); E. LEIBOWITZ and N. ROSEN: *Gen. Rel. Grav.*, **4**, 449 (1973); E. LEIBOWITZ: *Journ. Math. Phys.*, **15**, 313 (1973); G. ARCIDIACONO: *Relatività e Cosmologia* (Roma, 1973); R. L. INGRAHAM: *Nuovo Cimento*, **12**, 825 (1954). See also TH. KALUZA: *Sitzungsber. Preuss. Akad. Wiss. Berlin, Math. Phys. Kl.* (1921), p. 966; O. KLEIN: *Zeits. Phys.*, **37**, 895 (1926); A. EINSTEIN and P. BERGMAN: *Ann. Math.*, **39**, 683 (1938).

(12) Notice that, in our formalism, the strong conjugation \bar{C} is a unitary operator when acting on the state-space, as well as the strong time reversal \bar{T} .

(13) In the same way as—in 3-space—one can consider the components of velocity along the usual space axes, without introducing further « velocity axes ».

Let us now remember the relativistic result ⁽¹⁾ that the total reflection $\bar{P}\bar{T}$ is a proper transformation, *i.e.* a rotation; and let us apply it to quantum mechanics. It follows that, when acting on the state-space, the operator $\bar{P}\bar{T}$ is *unitary* (and not antiunitary, as was so far believed); in fact

$$(15) \quad + i \frac{\partial}{\partial x_\mu} \xrightarrow{\bar{P}\bar{T}} + i \frac{\partial}{\partial(-x_\mu)}.$$

Then, by applying the operator $CPT \equiv \bar{P}\bar{T}$ for instance to the fermion field ⁽¹⁴⁾ (and requiring as usual ⁽⁹⁾ Dirac-equation covariance) we get univocally

$$(16) \quad (\bar{P}\bar{T})^{-1}[\psi(-x_\mu, m_0)]\bar{P}\bar{T} \equiv P_5^{-1}[\psi(x_\mu, -m_0)]P_5 \equiv \gamma_5[\psi(x_\mu, m_0)].$$

Notice that, strictly speaking, the fifth axis corresponds to *proper mass* (or better to $m_0 c^2$) only in the momentum space; whilst, in the chronotopical space, the fifth axis should rather correspond to the canonically *conjugated* quantity ^(11,15), *i.e.* to *proper time* τ (cf. caption of fig. 2). And, *vice versa*, in quantum-mechanical language, the generator of infinitesimal translations along the fifth chronotopical co-ordinate τ ought to have suitable boundary conditions so to admit m_0 values as eigenvalues ⁽¹¹⁾. However, for physical clarity's sake, we shall go on writing down our symmetry considerations in terms of m_0 instead of τ , as allowed by our relativistic formalism ⁽¹⁴⁾. According to eq. (16), fermion *fields possess an interesting symmetry, expressed by the invariance*

$$(17) \quad \psi(-x_\mu, -m_0) \equiv \psi(x_\mu, m_0),$$

which—by the way—supports the idea that the 5-dimensional framework is more « complete » than the 4-dimensional one. Invariance (17) means that $\bar{P}\bar{T}P_5 \approx 1$ or better

$$(17 \text{ bis}) \quad \bar{P}\bar{T}P_5 \psi(\text{new co-ordinates}) = \psi(\text{old co-ordinates}).$$

These facts confirm—from the geometrical viewpoint—that chirality P_5 essentially means inversion of the fifth axis ^(10,11). Relation (17) means also that the physical description of a particle, *e.g.*, going « forward » in time and in space is *identical*—*i.e.* given in terms of the *same* functions—to the description of its antiparticle going backwards in time and in space.

⁽¹⁴⁾ Owing to the general validity of the starting philosophy ⁽¹⁾, the same will hold for any other field, too.

⁽¹⁵⁾ V. S. OLKHOVSKY and E. RECAMI: *Lett. Nuovo Cimento*, **4**, 1165 (1970); P. CALDIROLA: *Rend. Acc. d'Italia, Cl. Sc.*, **1**, 19 (1939).

Let us repeat that we are now in the presence of a 5-dimensional space and of 5-dimensional symmetries ^(10,11); see fig. 2. Then, let us consider in five dimensions inertial frames with a fifth axis (orthogonal to the 4-dimensional space), and represent a body by its space-time position *and* its rest mass. *From the frame with all the five axes inverted, an observer would describe « antimatter » exactly as the initial (noninverted) observer would describe matter.* Incidentally, such considerations help understanding the role of the « RIP »; and from eq. (4) we further get

(4bis)
$$\text{« RIP »} = P_5 X.$$

We can explicitly state the *theorem*: «(The functional forms of) *physical fields remain completely invariant under inversion of all five axes*»; cf. eq. (17). We have thus got a new, strong \overline{CPT} theorem, stating not only law covariance under \overline{CPT} , but even field *invariance* ⁽¹⁶⁾. The strong \overline{CPT} is a true *symmetry* operation of mechanics and electromagnetism (besides leaving the fields invariant).

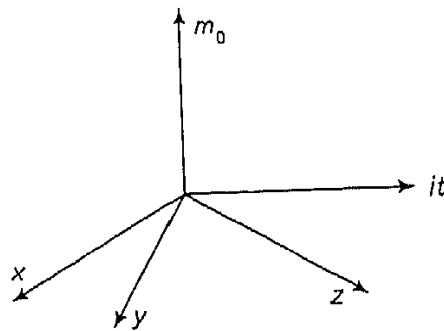


Fig. 2. — The 5-dimensional space (x, y, z, t, m_0) suggested by our symmetry investigation as the framework for relativistic mechanics and electromagnetism. The (quantized) fifth axis is connected with *proper mass*: see the text and ref. ^(10,11). Strictly speaking, *proper mass* (or better $m_0 c^2$) is the fifth axis in the momentum space; whilst, in the chronotopical one, the fifth axis should rather correspond to the quantity canonically conjugated to $m_0 c^2$, *i.e.* correspond to *proper time* τ .

In the relativistic, five-dimensional space, to each body can be attributed also some (new) quantized vectors having components only along the fifth axis m_0 and yielding—by their projections—mass and charges of the body.

Before closing, let us add the following observations:

- 1) We can consider the space (x, y, z, t, m_0) as the « complete » framework ⁽¹⁰⁾ for relativistic mechanics and electromagnetism, and realize that the

⁽¹⁶⁾ In four dimensions it is $\overline{PT} \equiv CPT = -1$ (4); analogously, in five dimensions $P_5 \overline{PT} \equiv \overline{CPT} = -1$ (5). MIGNANI and RECAMI ⁽¹⁾ have shown that within relativity physical laws are required to be covariant under $CPT \equiv \overline{PT}$. Here we show that under $P_5 \overline{PT} \equiv \overline{CPT}$ we have (besides mechanics and electromagnetism laws' covariance) even field invariance.

physical world is symmetric under total (5-dimensional) inversion. In particular, the Dirac equation turns out to be symmetric under our « five-inversion ».

2) Since fermion rest mass and antifermion rest mass have opposite signs, it follows that in any pair annihilation or pair creation process the rest mass behaves as a *conserved* (additive) charge, *i.e.* the rest mass is a conserved quantity *in those processes*; in such a case, leptonic and baryonic number conservations are well substituted by rest-mass conservation.

3) In ref. (9) it has been observed that *the product* of the Dirac equation and *antiequation*

$$(18) \quad i\gamma_\mu \frac{\partial}{\partial x_\mu} \psi(e^-) = m_0 \psi(e^-), \quad i\gamma^\mu \frac{\partial}{\partial x_\mu} \psi(e^+) = -m_0 \psi(e^+)$$

yields the Klein-Gordon equation. It suggests boson field space to be obtainable as a cross-product of the fermion and antifermion field spaces, in full agreement with the composition law of the corresponding spins.

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● RIASSUNTO

Si traggono alcune conseguenze dalle simmetrie spazio-temporali precedentemente studiate nell'ambito della relatività estesa, e si completa tale studio. In particolare si dimostra che la relatività richiede che le antiparticelle vengano formalmente associate a masse a riposo *negative* (ma, naturalmente, a masse relativistiche ed energie *positive*!). In tale contesto, si deriva quindi il significato fisico e geometrico della *chiralità* P_5 e si mostra che esso è essenzialmente connesso con l'inversione di un *quinto* asse (l'asse della massa a riposo). *In cinque dimensioni*, ad esempio, dal riferimento con tutti (i cinque) assi invertiti un osservatore descriverebbe l'*antimateria* esattamente come descriverebbe la *materia* dal riferimento iniziale (non invertito), e vice versa. Applicando quanto sopra alla meccanica quantistica relativistica (per esempio ai campi fermionici e all'equazione di Dirac), otteniamo — tra l'altro — un « teorema \overline{CPT} forte » (vedere il testo): « Nell'inversione di tutti e cinque gli assi x, y, z, t, m_0 , non solo restano covarianti le leggi fisiche (della meccanica e dell'elettromagnetismo, almeno), ma sono invarianti i campi fisici stessi ».

О новых симметриях пространства-времени в теории относительности и в квантовой механике.

Резюме (*). — Исследуются некоторые следствия симметрий пространства-времени, которые были рассмотрены ранее в обобщенной теории относительности. В частности, показывается, что теория относительности требует, чтобы античастицы были формально связаны с *отрицательными* массами покоя (но, конечно, с положительными релятивистскими массами и энергиями!). В этом контексте определяется физический и геометрический смысл *киральности*, P_5 . Показывается, что физический смысл киральности, по существу, связан с инверсией вдоль *пятой* оси (ось массы покоя). В *пяти измерениях*, в системе, где все (пять) осей инвертированы, наблюдатель описывает *антивещество* точно также, как исходный (неинвертированный) наблюдатель описывает вещество, и наоборот. Мы получаем «*сильную* \overline{CPT} теорему» (см. текст): «При инверсии всех пяти осей x, y, z, t, m_0 , не только физические законы (по крайней мере, механики и электромагнетизма) являются ковариантными, но и физические поля являются инвариантными».

(*) *Переведено редакцией.*