CHARGE CONJUGATION

A contribution to the history of this internal
quantum number of particle physics

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§1. One of the famous Dirac papers.

The existence of anti-matter is one of the few revolutionary concepts of twentieth century physics easily understood by the general public. Moreover it can be said exactly by whom and where existence of anti-matter was first predicted in print : by P.A.M. Dirac in the introduction of [1], paper sent on May 29, 1931 to the Royal Society and entitled "Quantized singularities in the Electromagnetic Field".

Let us summarize this introduction. The first paragraph begins with

> "The steady progress of physics requires for its formulation a mathemathics which is continuously more advanced"

and it is entirely devoted to the views of Dirac on this question

> ..."actually the modern developments have required a mathematics that continually shifts its foundation and gets more abstract"

and the last sentence of this first paragraph is :

> "It seems likely that this process of increasing abstraction will continue in the future and that advance in physics is to be associated with a continual modification and generalisation of the axioms at the base of mathematics rather than with a logical development of any mathematical scheme on a fixed foundation".

The second paragraph begins with

> "There are at present fundamental problems in theoretical physics awaiting solutions, e.g. the relativistic formulation of quantum mechanics and the nature of the atomic nuclei (to be followed by more difficult ones such as the problem of life), the solution of which problems will probably require a more drastic revision of our fundamental concepts than any that have gone before".

After explaining how he sees the future work in theoretical physics, Dirac comes back (3rd paragraph) to his previous paper [2], the one in which he introduced the Dirac equation : summarizing discussions on the consequences of this equation (that we shall review below) the author is led in the middle of the fourth paragraph to conclude to existence of

> "a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron".

He then explains that they do not occur naturally in Nature, they can be produced with an electron $2\gamma \to e^{+}+e^{-}$ (two photons create a pair) they can annihilate by the inverse reaction, they are stable in the vacuum.

The fifth paragraph is the shortest; in extenso :

> "The protons on the above view are quite unconnected with electrons. Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton. Theory at present is quite unable to suggest a reason why there should be any differences between electrons and protons".

Finally in the last paragraph (the sixth) of this introduction, Dirac present the subject of the paper. He would like to prove the relation

$$\hbar c/e^2 = 137 \tag{1}$$

but he will only explain the quantification

$$\hbar c/e\mu = 2 \tag{2}$$

where μ is the smallest strength of magnetic monopoles. Indeed this is the paper in which he introduces magnetic monopoles as quantized singularities of the electromagnetic field. In the conclusion he writes :

> "It is rather disappointing to find the reciprocity between electricity and magnetism, instead of a purely electronic quantum condition such as (1)".

I am sure we all feel disappointed that Professor Dirac has not been able to come to this conference. How much do we regret that he is not here to tell us these parts of history of science that he has made himself and to answer the many questions we would like to ask him.

So I feel very embarassed by giving this lecture on the history of "the charge conjugation". I am not a historian of physics and to prepare this text I did not work as an historian. I am here only as a witness : how I learned charge conjugation and lived as a physicist, the twenty-five years of this symmetry.

The titles of the paragraphs of this lecture are :

	chronology
1. One of the famous Dirac papers	1931
2. The prehistory of C	< 1931
3. The anti-matter	experimental evidence
4. The coming of age of C	1931-1937
5. The decadent years	1938-1951
6. C as internal quantum number	1950-1953

Since January 1957 we know that C is not an exact symmetry of the laws of Nature. In this meeting, this history will be told by professor V. Telegdi.

§2. The prehistory of C.

Charge conjugation symmetry is usually denoted by C. I learned that the existence of the two types of electricity was established experimentally by Charles François de Cisternay Du Fay (1698-1739). Cavendish precised the concept of positive and negative electricity. The Coulomb law is invariant by the change of sign of all electric charges. Assuming (Ampere hypothesis) that all electric currents are due to motion of electric charges, this invariance extends to Maxwell equations. Early in our century it was established that the elementary negative and positive electric charges are carried respectively by the electrons and the protons. Hence matter around us is not invariant by the symmetry C. And it became "clear" up to 1930 that the three constituents of our universe were : electrons (e^-) , protons (p^+) and photons (γ).

A relativistic quantum equation for a charged particle in an electromagnetic field has been studied by Gordon [3] and independently by Klein [4] at the end of 1926.* One year later Dirac wrote his paper "The quantum theory of the electron". He explains that the Gordon-Klein study has two important defects, i) it does not explain the "duplexity" of electron states which was related by Goudsmit and Uhlenbeck to the spin of the electron (an intrinsic angular momentum of value $\frac{1}{2}\hbar$), ii) it contains negative energy states; they do not need to be considered in a classical theory, but a quantum theory includes the possibility of jumps from positive to negative energy states. In the last paragraph of his introduction Dirac writes :

> "In the present paper we shall be concerned only with the removal of the first of these two difficulties".

This is done by application not only of the relativity principle (= Lorentz invariance) but also of the general transformation theory in quantum mechanics which requires that the wave function equation contains only first order time

* And before by Schrödinger, unpublished.

derivative. It leads to the Dirac equation. Dirac's book, in its several editions, use the very notation for the Dirac matrices which was introduced in the original paper : α, β and also ρ_i, σ_i $(i = 1,2,3)$. The original paper introduces also the "covariant notation" :

$$(i\Sigma\gamma_\mu p_\mu + m_c)\psi = 0 \qquad (3)$$

He studies the problem of an electron in a central potential, computes its angular momentum and for the Coulomb potential obtains the Darwin spectrum of bound state energies. In the paper with the same title, "part II" [2,b)] Dirac explains again his equation and studies the Zeeman effect.

The Dirac equation has been obtained from symmetry arguments only. What a success !

"§1. Nature of the Negative Energy Difficulty".

is the beginning of Dirac's paper [5] "A theory of electrons and protons" written nearly two years later. He first recalls the equation for the electron in an electromagnetic potential, which he writes in this paper (equation (1))

$$[\frac{W}{c} + \frac{e}{c} A_o + \rho_1(\underline{\sigma}.\underline{p} + \frac{e}{c}\underline{A}) + \rho_3 mc]\psi = 0 \qquad (4)$$

so $\rho_1\underline{\sigma} = \underline{\alpha}$, $\rho_3 = \beta$.

"In fact, if we take a matrix representation of the operators $\rho_1\sigma_1, \rho_1\sigma_2, \rho_1\sigma_3, \rho_3$ with the matrix elements all real, then the conjugate complex of any solution of (5) will be a solution of the wave equation obtained from (1) by reversal of the sign of the potential A and either the original wave function or its complex conjugate must refer to a negative E ".

Remark that instead of changing the sign of A , he could have changed the sign of e in (4)! But this would be artificial : e is the electron charge

Dirac uses several times italics in his text.

"Thus an electron with negative energy moves in an external field as though it carries a positive charge".

This result has led people to suspect a connection between the negative energy electron and the proton or hydrogen nucleus*"

* See for example Weyl 'Z.f. Phys', vol. 98, p.332 (1929).

However, Dirac explains, this would lead to three paradoxes : i) non conservation of electric charge in the transition from positive to negative energy state, ii) violation of equality of action and reaction, iii) negative energy electrons will have less and less energy the faster it moves, but

"No particles of this nature have been observed".

Thanks to Pauli's exclusion principle, Dirac proposes an alternative

"Let us assume... that all the states of negative energy are occupied except perhaps a few of small velocity"...

..."Only the small departures from exact uniformity, brought about by some of the negative-energy states being unoccupied, can we hope to observe..

"We are therefore led to the assumption that the holes in the distribution of negative-energy electrons are the protons. When an electron of positive energy drops into a hole and fills it up, we have an electron and proton disappearing together with emission of radiation".

Immediately Dirac goes to the difficulties. The infinite density of electric charge is troublesome for Maxwell equations.

"It is evident that the theory gives, to a large extent, symmetry between electrons and protons. We may interchange their roles and assert that the protons are the real particles and the electrons are merely holes in the distribution of protons of negative energy".

However Dirac points out - wrongly it seems - a possibility of asymmetry

"On the other hand, if we take the interaction between the electrons into account we get an extra term of the form ΣV_{ab} in the Hamiltonian, the summation being taken over all pairs of occupied states and this is not equivalent to any sum taken over pairs of unoccupied states.

and the concluding paragraph of this 2nd section :

"The consequences of this disymmetry are not very easy to calculate on relativistic lines, but we may hope it will lead eventually to an explanation of the different masses of proton and electron.

Possibly some more perfect theory of the interaction, based perhaps on Eddington calculation* of the fine structure constant e^2/hc is necessary before this result is obtained"

* Eddington 'Roy. Soc. Proc.' A, vol. 122, p.358 (1929).

Since electrons, protons and photons are the only known particles, the Dirac theory may yield a complete unification of physics, although there is much more to explain than the mass difference. Earlier in the paper :

"the power of protons to combine to form heavier atomic nuclei"

was another fact to explain.

The third section of this paper deals with scattering theory. In the Dirac theory the negative energy states played a necessary role. Dirac shows that the hole theory does not spoil the success of the earlier version because an electron from an occupied state can go to the final scattering state and the hole which is formed <u>virtually</u> can be occupied by the initial electron.

This ambitious theory was very short-lived! Criticisms came fast from Oppenheimer, [6a,b] , Tamm [7] and Dirac himself. In [6a] a one and a half page letter to the Physical Review, sent on February 14, 1930, Oppenheimer lists all the known objections ending by : the theory

> "gives a mean life time for ordinary matter of the order of 10^{-10} seconds.
>
> Thus we should hardly expect any states of negative energy to remain empty. If we return to the assumption of two independent elementary particles, of opposite charge and dissimilar mass, we can resolve all the difficulties raised in this note, and retain the hypothesis that the reason why no transitions to states of negative energy occur, either for electrons or protons, is that all such states are filled".

So physics is not unified, but Dirac theory is a good theory for the electrons and also for the protons! References [6b], [7], [8] give a detailed computation of the annihilation rate $e^{-}+p^{+} \to 2\gamma$ in the unified theory. Such a computation is ambiguous and requires artistic choices. That of Dirac is particularly interesting : he computes the annihilation rate for two particules with opposite electric charge and the <u>same mass</u> m . Alluding to the already quoted source of difference in the ΣV_{ab} term, he writes :

> "we cannot do better at present than to neglect the interaction all together, which entails working with a theory in which the electron and proton have the same mass".

H. Weyl had already changed his point of view and published [9] that Dirac's theory implied the same mass for the particles with opposite electric charge.

Two months after sending this paper [8] Dirac was sending the paper [1] predicting anti-electrons and anti-protons. I hope the historical path to this great discovery is now clearer for you all and we understand why Dirac had only to mention its discovery in the introduction of his next - and again very profound - paper devoted to another subject.

§3. The anti-matter.

In this monumental paper [1] in which Dirac invents anti-particles and magnetic poles he raises and tries to answer the question

"There remains to be discussed the question of why isolated magnetic poles are not observed".

Why did Dirac not ask the same question for anti-electrons ? I can quote as a detailed historical (and epistemological) study on the subject, the only book I have read : "The concept of positron" by Hanson [10] and I am completely puzzled by what Hanson says that Dirac told him, p.136 :

> "Professor P.A.M. Dirac once spoke to me of a lecture given at the Cavendish by D. Skobeltzyn 'some time in 1926 or 1927' ... an experimental set up within which Skobeltzyn was bombarding a metal target. One of the curiosities reportedly mentioned by Skobeltzyn was that several particles which were certainly electrons were seen to 'fall back into the source'; this despite the fact that most of the electrons moved in the way usual for this experiment, away from the source. Professor Dirac feels that what he remembers Skobeltzyn having then described could only have been positive electrons".

What seems well established is that in 1931 several experimentalists saw pairs of particles, with opposite electric charge, seemingly coming from a common origin. None of them quotes Dirac's paper [1] or, for those who interpreted the pair as e^-+p^+, Dirac's paper [5]. Although Oppenheimer sent his papers [6a,b] from "The Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena" where was working Anderson, the latter did not know Dirac's work, when he recognized a positron (i.e. positively charged electron) in his random expanded Wilson chamber. On August 2, 1932, assisted by Neddermeyer, he took a picture of a particle looking as an electron; but since it lost energy in the plate in the middle of the chamber, it was known coming from below (this is rare for a cosmic ray!) so it had to be positively charged. With other pictures (cosmic ray showers) confirming his interpretation, Anderson published his paper [11] in Science. In a counter-controlled cloud-chamber Blackett and Occhialini observed e^+e^- pairs in cosmic ray showers and quoted both Anderson and Dirac in their paper [12]. The two first observed anti-protons may have been seen in cosmic ray [13a,b] . The 6 GeV Berkeley Bevatron was built for making anti-protons. They were discovered [14] as expected, nearly 25 years after Dirac's prediction.

A few dozens anti-protons have recently been observed in cosmic rays. But it seems presently that there is not much anti-matter around us. Three years after the discovery of CP violation (see Prof. Fitch' lecture) Sakharov [15] proposed a tentative explanation of the disappearance of anti-matter from a C symmetric big bang. For that he had to add a rather bold hypothesis : nucleons can decay into mesons and leptons. For a different motivation there are now different experiments in progress for observing proton decay. Without success yet. However, Souriau [16] by mapping the known quasars in a Friedman universe have found a gap of quasars on a constant width (.8 billions light years) band around an equator which could be interpreted as the separation between two halves of our universe : one of matter, one of anti-matter. More observations are needed.

§4. The coming of the age of C (1932-1937).

The same month (January 1928) that Dirac had sent his paper on "the quantum theory of the electron" Jordan and Wigner [17] had sent their paper on second quantization for a Fermion field! So with the famous Dirac paper [1], quantum electrodynamics existed ! One could compute with confidence the cross section of phenomena (e.g. for pair production, the definitive work is [18]), study the infinities - and sometimes the radiative corrections. This would be a fascinating history to tell, but for lack of time we must strictly restrict ourselves to the subject. Let us note that in 1934 Heisenberg [19] introduces the manifestly C invariant symmetrized current operator while Pauli and Weisskopf [20] establish the second quantized theory of a zero spin charged particle in interaction with the electromagnetic field. This is manifestly a C invariant theory with no negative energies ! One can say that this is the solution of the second objection that Dirac raised in [2] against the Gordon-Klein equation. Is it possible to have fulfilled at once the two points of Dirac's program ? Yes answers Proca [21] in his paper "Sur la théorie ondulatoire des electrons positifs et negatifs" : but he writes the electromagnetic theory of spin one charged particles !

At last appeared the first theorem due to charge conjugation invariance proven in Furry's paper : "A Symmetry Theorem on the Positron Theory" [22] .

> "Theorem : In the calculations using plane wave functions as basis ("Born approximation") for processus in which the appearance of electrons and positrons is transitory only, the odd order contribution vanishes identically".

This explained why only even order terms appeared in perturbation theory calculations of scattering of light by a Coulomb field and photon-photon scattering. In modern notation : the contributions of electron closed loops with an odd number of (real or virtual) photons vanishes. Furry considers also the five covariants S,V,T,A,P of Dirac theory and shows that this cancellation occurs only for the vector V and tensor T interactions.

A very important step was the extension of the Dirac theory to neutrinos. This is done in 1934 by Fermi [23] in his paper on the theory of β-radioactivity. The theory is very similar to quantum electrodynamics except that the vector current of the electron-positron field is replaced by a charged vector current made with the electron and neutrino field containing the creation (or the annihilation) of an electron and a neutrino together for the β^--decay. While this paper was printed, in January 1934, Joliot-Curie discovered artificial β^+-radioactivity [24]. Immediately Wick [25] showed that this phenomenon was also included (symmetrically) by the Fermi theory. The fundamental process is $p \to n+e^+ + \bar{\nu}$, i.e. emission of an anti-electron and an anti-neutrino. Wick also predicted K-capture.

Finally explicit C symmetry quantum field theory for spin $\frac{1}{2}$ was described by Majorana [26] in 1937. His paper "Teoria simmetrica dell'electrone et del positrone" contains much more than suggested by the title. It is probably the first time that anti-commutation between the spinor field and its variation is taken in account for deriving the equations of motion from a Lagrangian. Then the second quantized theory for a Dirac field can proceed analoguously to the Pauli-Weisskopf quantization for spin 0 field, but using anti-commutators instead of commutators. There is no need to consider negative energy states : the vacuum is the zero particle state. Majorana concedes that this elegant version is physically equivalent to the Dirac hole theory. But it suggests an application : using for convenience a real representation of Dirac matrices, Majorana builds a quantum field theory of a true neutral particle without anti-particle, he suggests to apply it to

"neutrons and hypothetical neutrinos".

In the latter case, the only change to Fermi β-decay theory is that in β^- and β^+ the emitted neutrinos would be identical.

This Majorana paper was very soon followed in the same journal by a paper of Racah [27] "Sulla simmetria tra partielle e antipartielle". One of the conclusions of this paper is to reject the Majorana suggestion to apply his theory of neutral spin $\frac{1}{2}$ particle to neutrons because the neutron could not have a magnetic moment and it would decay with the same probability either into $p^+ + e^- + \nu$ or $p^- + e^+ + \nu$, which is against experimental evidence. A few months later a thorough study of C symmetry for a Dirac particle, independent from the Dirac matrix representation was made by Kramers [28]: "The use of charge-conjugated wave-functions in the hole theory of the electron". Among his results he proves that C commutes with any operation of the connected Lorentz group. However, there is a problem with the space reflection P, first studied in detail by Racah [27], relying on the excellent paper of Pauli [28] on the Dirac matrices(*). This would be a long story and Racah explains the difference of sign for terms proportional to neutrino mass between Fermi's paper [23] and [30a]. Racah was on the verge to show that in electrodynamics C and P do not commute; so the intrinsic parity of particles and anti-particles are opposite. I do not know who first proved it.

§5. The decadent years (1938-1950).

C invariance did not attract much attention. Many theorists violated it unconsciously. For instance, in an important and influential paper Kemmer [31] considers the most general interaction between a Dirac field (nucleon) and a

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(*) The Pauli notations were the most usual ones up to Schwinger's papers in 1948-49 who changed all notations and did not quote previous works.

boson field of spin 0 or 1 . Along the five Dirac covariant S,V,T,A,P , made from the Dirac field ψ and its Hermitean conjugate, it was known [22], [29] that only V and T are odd by charge conjugation; it was overlooked by Kemmer that the sum of the two couplings :

$$f\phi S + gV^\mu \frac{\partial\phi}{\partial x^\mu} \qquad \text{for a scalar meson field } \phi$$

$$g\epsilon_{\mu\nu\rho\sigma} \frac{\partial\phi^\mu}{\partial x_\nu} T^{\rho\sigma} + f\phi^\mu A_\mu \qquad \text{for a pseudo vector field } \phi^\mu$$

violates C . It also violates time reversal T (see Doncel's conference in these proceedings) since it preserves CPT . There is no point to give here a long (and surely incomplete) list of physics papers violating C (and generally also T); there were many in the late forties, more specially those dealing with β-decay. The elegant C-symmetry formalism of Majorana was forgotten. I had learned it and I must say I was - and I am presently - somewhat puzzled that in the third edition of his fundamental book [32], in 1947, Professor Dirac still used his hole theory for "§73 Theory of the positron", specifying that

> "The infinite distribution of negative electrons do not contribute to the electric field".

Even Fermi's paper [23] was not completely understood because he described the decay $n \to p^+ + e^- + \nu$ as an absorption of one particle and the creation of three. Most β-decay papers preferred to consider it as a charge exchange scattering (without second quantization) of a neutron and a negative energy neutrino yielding a proton and an electron and, a hole in the sea of negative energy neutrino (as was done in [30]). This hole was called antineutrino ν and this is the convention (and not that of Fermi) which has survived today, assuming that the neutrinos are not Majorana neutrinos. Racah, in the paper [27] already quoted has given a physical difference between the two possibilities; the neutrino ν_- emitted in β-decay can induce only the reaction $\nu_- + p^+ \to n + e^+$ if it has an anti-particle while it has an equal probability to induce also $\nu_{-}+n \rightarrow p^{+}+e^{-}$ if it is a Majorana particle. Furry [32] proposed another test : as soon as 1935 M. Goeppert-Mayer had remarked that many nuclei were unstable by second order β-decay $(Z,N) \rightarrow (Z+2,N-2) + 2e^{-}+2\nu$. Furry suggested to look for the much faster process $(Z,N) \rightarrow (Z+2,N-2)+2e^{-}$ which will instead occur if neutrinos are Majorana particles. In 1949 I also discussed [34] the nature of the neutrinos emitted in μ-decay : $\mu \rightarrow e+2\nu$. In the following years, too many papers predicted wrong effects for Majorana neutrino due to a misunderstanding of this theory, that is essentially a second quantization theory, but was applied in the frame of a simple scattering à la Konopinski-Uhlenbeck [30]. With P and C violation, (see the Telegdi lecture) if the neutrinos are massless, they are completely polarized circularly and it may become meaningless to distinguish between Majorana 4-component neutrino field and Dirac 2 component neutrino-anti-neutrino field. (An interesting paper on this point written in 1952 is that of Serpe [35]). Presently we do know that there are different kinds of neutrinos; we ignore the values of their mass, we are puzzled by the apparently low neutrino flux from the sun and we are also looking for the possibility of $\nu-\bar{\nu}$ oscillations !

§6. C - as internal quantum number (1949-53)

We call internal quantum numbers of particle physics those who do not derive from kinematical invariance : the full Poincaré group including P and T . The gauge group invariance U(1) which implies charge conservation is one example, C is the second example. Another example of internal quantum is isotopic spin, invented by Heisenberg [36] in 1932; its early history has been written by Rasche [37]; see also Mukherji [38] and for a more complete history, the recent paper of Kemmer [39] who was the author in 1938 of the classic paper

[40]"The charge-dependence of nuclear forces" where a triplet of isospin 1 meson is introduced.

It is only in 1949 that the Furry theorem was extended to include photons and isospin 1 mesons. This was done by Fukuda, Mujamoto [41a] with Hayakawa [41b] and by Sasaki, Oneda, Ozaki [42] and also by Van Wyk [43] and completed by my paper [44] where an even more complete list of references can be found. I also extended it to Fermi weak interaction (e.g. in $\pi \rightarrow \mu\nu$ decay) and distinguished two types of weak terms by their symmetry under the product of P and isotopic parity (defined below) (called now 1st and 2nd class weak currents).

A perturbation independent treatment was made by Nishijima [45] for the rules proved in [41-43] and for all possible rules by the union of the three papers, Pais-Jost [46], Wolfenstein and Ravenhall [47], Michel [48]. If historians of science are interested by the subject they can concentrate first on these three papers. With the short recent historical exposition by Nishijima [49] they probably contain all relevant references. They may wonder why it took four years to clear up this simple subject : simply because average physicists are slow to understand. Another proof of that is the time delay necessary to the community at large to assimilate the new concepts (few years in that case).

May I give very shortly here my reminiscences (wishing that the other authors will also do it somewhere) ? I was working mainly on universal Fermi-interaction, but in Spring 1952 I had written two notes in Comptes Rendus on selection rules due to Poincaré invariance and I got interested by those due to C . I wrote a paper on it at Les Houches Summer School where I spent the summer (and I was awarded for it the Stakhanov prize at the last party of the session!). Then I discussed about it with Wolfenstein and also with Gell-Mann. The opinion of Weisskopf was asked on my paper; he wrote advising me not to publish it. How lucky I have been to receive this wise advice. Pais and Jost had sent me their preprint in which they acknowlegde my previous work [44] and rightly critizise it; this induced me to work again on the combination of C and isospin. When I arrived in Copenhagen for eight months (the first year of the theoretical study group of CERN) I gave a seminar on it and benefited from remarks by Mottelson. I had papers [46] and [47] when I wrote mine, so I could expand the applications they had not treated (e.g. nucleon - anti-nucleon annihilation) and aim at completeness and at a more or less definitive presentation. My treatment was by abstract group theory (very elementary by to-day standard) but I introduced the operator $U = CM = MC$ where M is the rotation by π around the second axis in isotopic space and verified explicitly its commutation with all isospin rotations. So I identified it with the parity operator

> "With the convention of this paragraph, U , the inversion through the origin in isotopic space has the eigenvalue $t = \varepsilon(-1)^J$. This is the "parity" in isotopic space"

(J was the isospin and ε the eigenvalue of C for the $J_3 = 0$ component) The last of the two sentences of the abstract reads :

> "It is shown that when isotopic spin formalism is used, invariance under charge conjugation corresponds to conservation of isotopic parity".

and near the end of the introduction :

> "To include charge conjugation considerations in the study of π-mesons (assumed to be pseudoscalar symmetric), one shall consider them as <u>polar</u> vectors in isotopic space".

In this paper I considered only the "usual meson theories". But in my contribution [50] to the International Cosmic Ray conference (Bagneres de Bigorre, 1953) I dealt with all possible sets of mesons, defined only by their quantum numbers and applied it to the newly found particles.

More than two years after, in the same journal, three papers appear containing the selection rules for the annihilation nucleon-anti-nucleon : Amati and Vitale [51], Lee and Yang [52] and Bethe and Hamilton [53] (this paper contains mainly a dynamical model). As Lee and Yang said in their footnote 3.

"Most of these results have been stated in literature in various forms"

(and they quote papers [46], [47], [48], [51]). Indeed the only original parts of their paper are the last seven lines, which introduce strangeness in the game, and the use of the symbol G for isoparity.

Why do so many physicists use the unexpressive G (e.g. the Review of Particle Properties [54] which is the basis of the Data booklet carried in the pocket of every high energy physicist) instead of the exact expression "isoparity" ? (*) I feel it is bad taste. But as a member of the rich, large, lively - and sometimes petulant - tribe of particle physicists I love it as it is, with its breakings and its defects (as for the symmetries [56]). In this tribe I found some very kind elders who guided me, and many good friends of different generations. They all helped me to understand physics. I thank them all.

I am very grateful to my friend M.C. Doncel for planning and organizing such a stimulating meeting between physicists and historians of science.

(*) Wick, in a review paper [55] where he quotes only Lee-Yang and Bethe-Hamilton, proposes the name isotopic parity (his § 6.5), but his suggestion was not more followed than mine.

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Last addition. Professor A. Krisch just sent me the text of "The first Crane Lecture" delivered by Professor P.A.M. Dirac on April 17, 1978 at the University of Michigan, Ann Arbor. Its title was "The Prediction of Anti-matter".