

**Zeitschrift:** Helvetica Physica Acta  
**Band:** 33 (1960)  
**Heft:** VIII

**Artikel:** Space time reflexions, light quanta and heavy bosons  
**Autor:** Fröhlich, H.  
**DOI:** <https://doi.org/10.5169/seals-113097>

### **Nutzungsbedingungen**

Die ETH-Bibliothek ist die Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Zeitschriften und ist nicht verantwortlich für deren Inhalte. Die Rechte liegen in der Regel bei den Herausgebern beziehungsweise den externen Rechteinhabern. [Siehe Rechtliche Hinweise.](#)

### **Conditions d'utilisation**

L'ETH Library est le fournisseur des revues numérisées. Elle ne détient aucun droit d'auteur sur les revues et n'est pas responsable de leur contenu. En règle générale, les droits sont détenus par les éditeurs ou les détenteurs de droits externes. [Voir Informations légales.](#)

### **Terms of use**

The ETH Library is the provider of the digitised journals. It does not own any copyrights to the journals and is not responsible for their content. The rights usually lie with the publishers or the external rights holders. [See Legal notice.](#)

**Download PDF:** 21.12.2024

**ETH-Bibliothek Zürich, E-Periodica, <https://www.e-periodica.ch>**

## Space time reflexions, light quanta and heavy bosons

by **H. Fröhlich**

Department of Theoretical Physics, University of Liverpool

*Summary.* A new approach to space time reflexions leads to the introduction of a new angular space in terms of which isobaric spin and related quantities find a simple explanation. On the basis of this new treatment a wave equation is presented which contains as specific cases the Maxwell equations, and the wave equations for  $\pi$ - and  $K$ -mesons. It also predicts the existence of a further particle with mechanical spin 1, with the same isobaric spin properties as  $K$ -mesons but with a larger rest mass.

### 1. Introduction

During a number of years reflexions of various kinds—space, time, charge—have been considered as very important for an understanding of fundamental particles. I feel that the usual treatment of such reflexions is open to serious criticism and I shall show that an appropriate change leads to the introduction of a new angular space in terms of which reflexions can be considered as special cases of continuous transformations. This new space offers an understanding of isobaric spin and related quantities and possibly also of rest mass. The great concern which W. PAULI showed for the treatment of reflexions makes it appropriate to discuss these new possibilities in the present memorial issue.

Consider first as a very simple example a two dimensional space with a coordinate frame  $x, y$  and an irregular triangle in it described by the coordinates of three points  $(x_1, y_1), (x_2, y_2), (x_3, y_3)$ . A rotation replaces these three by three different coordinate pairs  $(x'_k, y'_k)$ . Such a transformation can be interpreted in two different ways as is well known from geometry: (i) the triangle has not been moved, but the frame has been rotated; (ii) the frame remains the same but the triangle has been moved. The first interpretation has no physical (geometric) meaning in terms of the figure for a coordinate system is quite an arbitrary device. The second interpretation, however, has a very definite physical meaning connected with the displacement of the figure in space. To have a closer analogy with field equations we replace the triangles by the three straight lines forming it. They are described by three equations between  $y$  and  $x$ ,  $a_k x + b_k y + c_k = 0$ . Rotation of the coordinate frame by an angle  $\gamma$

(first interpretation) corresponds to a replacement of  $(x, y)$  by  $(x', y')$ , say,  $x = x' \cos \gamma - y' \sin \gamma$ ;  $y = x' \sin \gamma + y' \cos \gamma$ . The appropriate motion of the triangle on the other hand corresponds to a replacement of  $a_k, b_k$  by  $a'_k = a_k \cos \gamma + b_k \sin \gamma$ ;  $b'_k = -a_k \sin \gamma + b_k \cos \gamma$  (second interpretation). Carried out together the two transformations leave the form of the equations invariant.

Consider now a reflexion in which each  $x$  coordinate is replaced by its negative. According to the first interpretation we simply have replaced the original frame by another one. Since a frame is an arbitrary device such a change is, of course, always possible. The second, physical, interpretation is, however, no longer possible in a simple manner unless we extend the whole mode of description of the triangle. One such possibility would be the introduction of 'internal' coordinates permitting the triangle to be turned inside out (or rather its two dimensional analogue). Another possibility arises, however, if we permit the triangle to leave the  $x - y$  plane by rotating it around the  $y$ -axis. This requires the introduction of a new dimension, an angle  $\theta$ . The case  $\theta = 0$  then would correspond to the original triangle, and  $\theta = 180^\circ$  to its mirror image. Invariance of the above three equations under reflexion thus involves (i) replacement of the coordinate frame  $(x, y)$  by  $(-x, y)$  and (ii) rotation of the triangle around the  $y$  axis by  $180^\circ$ , leading to the replacement of  $a_k$  by  $-a_k$ .

Interpretation of the angle  $\theta$  in terms of the  $x - y$  plane suggests a formal connection with Pauli spin operators. The cases  $\theta = 0$  and  $\theta = 180^\circ$  describing the original triangle and its reflected one would correspond to the two opposite directions of the spin.  $\theta = 90^\circ$  would then be interpreted as an appropriate mixture of these two cases.

Following the above discussion I feel that point transformations other than mere coordinate replacements should be considered as unphysical and should be replaced by continuous transformations through introduction of new angular coordinates (or of internal coordinates; this will not be done here). To introduce such a new description consider a four-vector field  $V_\mu$  (space components  $V_k$ , time component  $V_0$ ) in a Lorentz frame  $x_\mu$  ( $\mu = 1, 2, 3, 4$ ;  $x_4 = i x_0$ ) and introduce three operators  $\Pi_l(\Omega)$ ,  $l = 1, 2, 3$  which depend on angles  $\Omega$  in a way specified below. We then replace the  $V_\mu$  by

$$(V_k, V_0) \rightarrow (\Pi_1 V_k, i \Pi_2 V_0) \quad (1.1)$$

and demand that

$$\Pi_1^2 = 1, \quad \Pi_2^2 = 1, \quad \Pi_3^2 = 1, \quad (1.2)$$

so that the length is given by

$$(\Pi_1 V_k)^2 + (i \Pi_2 V_0)^2 = V_k^2 - V_0^2 = V_k^2 + V_4^2. \quad (1.3)$$

Secondly we demand that the  $\Pi_l$  are invariant under continuous Lorentz transformations to that  $\Pi_1$  is always connected with space,  $i\Pi_2$  with time components. This is possible only if the relative velocity  $v$  entering the transformation is also replaced by an operator

$$v \rightarrow \Pi_3 v \quad \text{i. e.} \quad (\Pi_3 v)^2 = v^2. \quad (1.4)$$

A typical Lorentz transformation leading to relative motion in the 3-direction transforms  $V_\mu$  into  $V'_\mu$ . With the replacement (1.1), (1.4) and the requirement on  $\Pi_1$  and  $\Pi_2$  then

$$\left. \begin{aligned} (1 - v^2)^{1/2} \Pi_1 V'_3 &= \Pi_1 V_3 - \Pi_3 v (i\Pi_2) V_0 = \Pi_1 (V_3 - v V_0) \\ (1 - v^2)^{1/2} i\Pi_2 V'_0 &= -\Pi_3 v \Pi_1 V_3 + i\Pi_2 V_0 = i\Pi_2 (-v V_3 + V_0) \end{aligned} \right\} (1.5)$$

must hold. This is possible only if (cycl. means cyclic permutation of the suffixes 1, 2, 3)

$$i\Pi_3 = \Pi_1 \Pi_2, \quad \Pi_1 \Pi_2 + \Pi_2 \Pi_1 = 0, \quad \text{cycl.} \quad (1.6)$$

Thus, as a consequence of the consistency conditions expressed by equations (1.5) the  $\Pi_l$  must satisfy the Pauli anticommutation rules. One might, at first sight, expect that  $\Pi_l = 1$  should satisfy consistency. This trivial possibility was excluded by the replacement of the time component  $V_0$  by  $i\Pi_2 V_0$  which in view of  $\Pi_2^2 = 1$  thus represents not an hermitean but an antihermitean operator. There is no reason why such operators should not be introduced provided that measurable quantities are described in terms of hermitean operators. It will be discussed in § 6 that this actually is the case. The introduction of the antihermitean operator  $i\Pi_2$  has been postulated above with the purpose of obtaining a non trivial extension of the previous description of four-vector fields. It touches no doubt, however, on the very deep difference between space and time components whenever questions of reflexion are concerned.

Conditions (1.6) are, of course, fulfilled by Pauli matrices  $a_l$  (or  $\mathbf{a}$ ) (dots and empty spaces represent zeros)

$$a_1 = \begin{pmatrix} \cdot & 1 \\ 1 & \cdot \end{pmatrix}, \quad a_2 = \begin{pmatrix} \cdot & -i \\ i & \cdot \end{pmatrix}, \quad a_3 = \begin{pmatrix} 1 & \\ & -1 \end{pmatrix}. \quad (1.7)$$

The conditions (1.6) are also satisfied by other matrices obtained from (1.7) by unitary transformations\*). We therefore assume for the  $\Pi_l$ ,

$$\Pi_l = s^{-1} a_l s \quad (1.8)$$

where  $s$  is unitary. In its most general form,  $s$  and hence  $\Pi_l$  depend on three real parameters which can be expressed in terms of Eulerian angles  $\Omega = (\theta, \chi, \varphi)$  by

\*) More general transformations will not be considered.

$$s = e^{i \frac{\varphi}{2} a_3} e^{i \frac{\theta}{2} a_2} e^{i \frac{\chi}{2} a_3} = e^{i \frac{\theta}{2} a_2} e^{i \frac{\chi}{2} a_3} e^{i \frac{\varphi}{2} a_3} \quad \left. \vphantom{s} \right\} (1.9)$$

$$0 \leq (\chi, \varphi) \leq 2\pi, \quad 0 \leq \theta \leq \pi$$

Eulerian angles are well known from the theory of spinning tops. They are defined in terms of an orthogonal frame (the external frame) in which the vector operator  $\mathbf{a}$  has the three components  $a_l$ . The Eulerian angles then define three orthogonal unit vectors  $\mathbf{u}_l$  (the inner frame;  $\mathbf{u}_3$  is denoted as figure axis) such that

$$\Pi_l = (\mathbf{a} \mathbf{u}_l) \quad (1.10)$$

In the external frame the  $\mathbf{u}_l$  have the following components,

$$\left. \begin{aligned} \mathbf{u}_1 &= (\cos\theta \cos\chi \cos\varphi - \sin\chi \sin\varphi, \quad \cos\theta \sin\chi \cos\varphi + \cos\chi \sin\varphi, \\ &\quad -\sin\theta \cos\varphi) \\ \mathbf{u}_2 &= (-\cos\theta \cos\chi \sin\varphi - \sin\chi \cos\varphi, \\ &\quad -\cos\theta \sin\chi \sin\varphi + \cos\chi \cos\varphi, \quad \sin\theta \sin\varphi) \\ \mathbf{u}_3 &= (\sin\theta \cos\chi, \quad \sin\theta \sin\chi, \quad \cos\theta). \end{aligned} \right\} (1.11)$$

Each  $\Pi_l$  can be considered as invariant under rotation of the external frame, being the inner product of two vectors  $\mathbf{a}$  and  $\mathbf{u}_l$ . Rotation then implies an unitary transformation acting on the  $\mathbf{a}$  followed by a rotation of the  $\mathbf{u}_l$  i.e. an appropriate change of the angles  $\Omega$ . This invariance of the  $\Pi_l$  means that each replacement of  $\Omega$  by  $\Omega_1$ , say, can alternatively be expressed in terms of an appropriate unitary transformation. Thus unitary transformation by  $\Pi_2$  which in view of  $\Pi_2 \Pi_1 \Pi_2 = -\Pi_1$  leads to space reflexion is equivalent to the replacement of  $\Omega = (\theta, \chi, \varphi)$  by  $\Omega_1 = (\pi - \theta, \chi - \pi, \pi - \varphi)$ . For with (1.11) one finds  $\Pi_1(\Omega_1) = -\Pi_1(\Omega)$ ;  $\Pi_2(\Omega_1) = \Pi_2(\Omega)$ .

To illustrate the new treatment we investigate the vector field  $\Pi_1 \hat{p}_k \psi$ ,  $i \Pi_2 \hat{p}_0 \psi$  of the momentum vector, where  $\psi(x_\mu, \Omega)$  is a two component function and  $\hat{p}_\mu = -i \partial_\mu$ .  $\psi$  can be classified in terms of Pauli spinors  $\xi(\Pi)$ ,  $\eta(\Pi)$  satisfying

$$\left. \begin{aligned} \Pi_1 \xi(\Pi) &= \eta(\Pi), \quad \Pi_1 \eta(\Pi) = \xi(\Pi); \quad \Pi_2 \xi(\pi) = +i \eta(\Pi), \\ \Pi_2 \eta(\Pi) &= -i \xi(\Pi); \quad \Pi_3 \xi(\Pi) = \xi(\Pi), \quad \Pi_3 \eta(\Pi) = -\eta(\Pi). \end{aligned} \right\} (1.12)$$

From (1.8) and (1.7) therefore

$$\left. \begin{aligned} \xi(\Pi) &= s^{-1} \xi(a), \quad \eta(\Pi) = s^{-1} \eta(a), \\ &\text{where } \xi(a) = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \eta(a) = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{aligned} \right\} (1.13)$$

Let now

$$\left. \begin{aligned} \psi_+(x, \Omega) &= \frac{1}{\sqrt{2}} (\xi(\Pi) + \eta(\Pi)) e^{iK_\mu x^\mu}, \\ \psi_-(x, \Omega) &= \frac{1}{\sqrt{2}} (\xi(\Pi) - \eta(\Pi)) e^{iK_\mu x^\mu}. \end{aligned} \right\} (1.14)$$

The two cases  $\psi_+$  and  $\psi_-$  correspond thus to vector fields with space components  $+K_k \psi_+$  and  $-K_k \psi_-$  respectively. A similar separation of the time component into a forward ( $+K_0$ ) and backward ( $-K_0$ ) field is not possible. In fact  $\xi(\Pi) \pm i\eta(\Pi)$  which would diagonalise  $i\Pi_2$  has imaginary eigenvalues which indicates that for a single vector field the decision whether the time component runs forward or backward is not a measurable quantity. The case of two vector fields is quite different, as will be shown in the following (in particular § 6). Here a measurable quantity exists which compares the direction of the time components of the two fields. It measures whether for the two these directions are equal, or opposite.

Finally, we show that space reflexion represents now a special case of the continuous unitary transformation by

$$e^{i\frac{\vartheta}{2}\Pi_2} = \cos\frac{\vartheta}{2} + i\Pi_2 \sin\frac{\vartheta}{2}. \quad (1.17)$$

It yields

$$e^{i\frac{\vartheta}{2}\Pi_2} \Pi_1 e^{-i\frac{\vartheta}{2}\Pi_2} = \Pi_1 \cos\vartheta + \Pi_3 \sin\vartheta \quad (1.18)$$

and

$$e^{i\frac{\vartheta}{2}\Pi_2} \psi_\pm = \cos\frac{\vartheta}{2} \psi_\pm + \sin\frac{\vartheta}{2} \psi_\mp. \quad (1.19)$$

Clearly  $\vartheta = 180^\circ$ , transforms  $\Pi_1$  into  $-\Pi_1$  and hence reflects the space component  $\Pi_1 p_k$ .

In the following sections the ideas discussed here will be applied to the wave equation of bosons. On some simple assumptions it will be seen that from a single wave equation we obtain as special solutions the Maxwell equations, the equations for  $\pi$ - and  $K$ -mesons together with the correct isobaric spin assignments. We also predict existence of a particle with mechanical spin 1, with equal isobaric spin properties as  $K$ -mesons, but with larger rest mass.

Some of the following developments (§§ 2 and 3) have been presented before<sup>1)</sup> though in a less systematic form.

## 2. The Wave Equation of Bosons

Relativistic wave equations are based on the identity ( $\kappa$  = rest mass, units  $\hbar = 1, c = 1$ )

$$p_\mu v_\mu + \kappa = p_k v_k - p_0 v_0 + \kappa = 0 \quad (2.1)$$

Here  $v_\mu$  is the four-velocity which in contrast to classical physics is defined independently of the four-momentum  $p_\mu$  in terms of certain operators, namely

$$p_\mu = -i\partial_\mu \quad (2 \cdot 2), \quad v_\mu = i\beta_\mu. \quad (2.3)$$

For bosons, following KEMMER<sup>2)</sup> the  $\beta_\mu$  satisfy the algebraic relations

$$\beta_\mu \beta_\nu \beta_\rho + \beta_\rho \beta_\nu \beta_\mu = \delta_{\mu\nu} \beta_\rho + \delta_{\rho\nu} \beta_\mu. \quad (2.4)$$

In contrast to KEMMER, however, the  $\beta_\mu$  will be defined more explicitly in terms of two pairs of Pauli spins,  $\varrho_k, \varrho'_k; \sigma_k, \sigma'_k$  by

$$\beta_k = \frac{1}{2} (\varrho_1 \sigma_k + \varrho'_1 \sigma'_k), \quad \beta_4 = \frac{1}{2} (\varrho_2 + \varrho'_2) \quad (2.5)$$

They are thus  $16 \times 16$  matrices.

Our new treatment of four vectors requires the replacements (1.1) for both  $v_\mu$  and  $p_\mu$ . The independent definition of these quantities requires two sets of  $\Pi_l(\Omega)$ 's, say  $\Pi_l(\Omega)$  and  $\Pi'_l(\Omega')$  so that

$$p_k \rightarrow \Pi_1(\Omega) p_k, \quad p_0 \rightarrow i \Pi_2(\Omega) p_0 \quad (2.6)$$

$$v_k \rightarrow \Pi'_1(\Omega') v_k, \quad v_0 \rightarrow i \Pi'_2(\Omega') v_0. \quad (2.7)$$

Furthermore, since the length of a four vector is defined by (1.3) the product of two four vectors is given by

$$\left. \begin{aligned} p_\mu v_\mu &\rightarrow (\Pi_1 p_k) (\Pi'_1 v_k) + (i \Pi_2 p_0) (i \Pi'_2 v_0) = \\ &= \Pi_1 \Pi'_1 p_k v_k - \Pi_2 \Pi'_2 p_0 v_0 = \Pi_1 \Pi'_1 p_k v_k + \Pi_2 \Pi'_2 p_4 v_4. \end{aligned} \right\} \quad (2.8)$$

Making now the replacements (2.8), (2.2), (2.3), (2.5) in (2.1) leads to the wave equation

$$B_\mu \partial_\mu + M, \Psi = 0 \quad (2.9)$$

where

$$\left. \begin{aligned} B_k &= \frac{1}{2} \Pi_1(\Omega) \Pi'_1(\Omega') (\varrho_1 \sigma_k + \varrho'_1 \sigma'_k), \\ B_4 &= \frac{1}{2} \Pi_2(\Omega) \Pi'_2(\Omega') (\varrho_2 + \varrho'_2) \end{aligned} \right\} \quad (2.10)$$

Here the rest mass  $\varkappa$  has also been replaced by a mass operator  $M$  which will be discussed below. The  $B_\mu$  are thus  $64 \times 64$  matrices but such a matrix representation will never be required. The adjoint equation to (2.9) is given by

$$\bar{\Psi}, \quad B_\mu \partial_\mu - M = 0 \quad (2.11)$$

where  $(\Psi^+$  is the hermitean conjugate of  $\Psi)$

$$\bar{\Psi} = \Psi^+ R_2 \tag{2.12}$$

and

$$R_1 = -\varrho_1 \varrho'_1, \quad R_2 = -\varrho_2 \varrho'_2, \quad R_3 = -\varrho_3 \varrho_3 \tag{2.13}$$

i. e.

$$R_1 R_2 = R_3, \quad R_1^2 = 1, \quad \text{cycl.} \tag{2.14}$$

It will be noticed that the wave equation depends on three pairs of Pauli spins,  $(\Pi_l, \Pi'_l), (\varrho_k, \varrho'_k), (\sigma_k, \sigma'_k)$ . The solutions will be discussed in terms of appropriate spin functions. For this purpose we introduce for each pair Pauli spinors  $\xi, \eta; \xi', \eta'$  similar to (1.12). In case of ambiguity they will be denoted by  $\xi(a), \xi(\Pi)$  etc., if they refer to Pauli matrices  $a, \Pi$ , etc. Three symmetrical spin pair functions  $\Sigma_l$  and one antisymmetric  $\Sigma_4$ , can then be introduced by

$$\left. \begin{aligned} \Sigma_1 &= -\frac{i}{\sqrt{2}} (\xi\xi' - \eta\eta'), & \Sigma_2 &= -\frac{1}{\sqrt{2}} (\xi\xi' + \eta\eta'), \\ \Sigma_3 &= \frac{i}{\sqrt{2}} (\xi\eta' + \eta\xi') \end{aligned} \right\} \tag{2.15}$$

and

$$\Sigma_4 = \frac{i}{\sqrt{2}} (\xi\eta' - \eta\xi'). \tag{2.16}$$

They are orthogonal and normalised. In case of ambiguity they are denoted by  $\Sigma_\sigma(a), \Sigma_\sigma(\Pi), \Sigma_\sigma(\varrho), \Sigma_\sigma(\sigma)$ , if they refer to the pairs  $a, \Pi, \varrho, \sigma$  respectively. They have been chosen such as to diagonalise the three  $R_k$  (2.13) or the corresponding  $\Pi, \sigma, a$  quantities—as shown in table 1.

Table 1  
Eigenvalues of  $R_k$

	$\Sigma_1$	$\Sigma_2$	$\Sigma_3$	$\Sigma_4$
$R_1$	1	-1	-1	1
$R_2$	-1	1	-1	1
$R_3$	-1	-1	1	1

It follows from the above that a total of  $4^3 = 64$  orthogonal normalised spin functions exist. In a matrix representation each would be represented by a column matrix containing 63 zeros and a one, the latter in a different place for each of the 64 functions.

We consider now first the 16 functions  $\Sigma(\varrho) \Sigma(\sigma)$  referring to the  $\varrho$  and  $\sigma$ 's, i. e. to the  $\beta_\mu$  alone. Under exchange of dashed and undashed oper-



ators we find 10 symmetrical functions  $\Gamma_s$  and six antisymmetric ones  $\Gamma_a$ . Of the latter  $\Sigma_2(\varrho) \Sigma_4(\sigma)$  is of no interest because

$$\beta_\mu \Sigma_2(\varrho) \Sigma_4(\sigma) = 0 \tag{2.17}$$

for all four  $\beta_\mu$ . The remaining five antisymmetric functions are

$$\left. \begin{aligned} \Gamma_a(k) &= \Sigma_4(\varrho) \Sigma_k(\sigma), & k &= 1, 2, 3 \\ \Gamma_a(4) &= \Sigma_3(\varrho) \Sigma_4(\sigma), & \Gamma_a(5) &= \Sigma_1(\varrho) \Sigma_4(\sigma) \end{aligned} \right\} \tag{2.18}$$

The ten symmetric functions will be denoted as follows

$$\left. \begin{aligned} \Gamma_s(E_k) &= \Sigma_1(\varrho) \Sigma_k(\sigma), & \Gamma_s(H_k) &= \Sigma_2(\varrho) \Sigma_k(\sigma) \\ \Gamma_s(\phi_k) &= -\Sigma_3(\varrho) \Sigma_k(\sigma), & \Gamma_s(\phi_4) &= \Sigma_4(\varrho) \Sigma_4(\sigma) \end{aligned} \right\} \tag{2.19}$$

The action of the  $\beta_\mu$  on these sixteen functions can be seen in a simple way from  $5 \times 5$  and  $10 \times 10$  matrix representations denoted as  $\beta_\mu(5)$  and  $\beta_\mu(10)$  respectively. In the former  $\Gamma_a(\beta)$ ,  $\beta = 1, 2 \dots 5$ , are column matrices with zero's except with a one at the  $\beta$ -th row. This implies that

$$\left. \begin{aligned} \beta_1(5) &= \left( \begin{array}{c|c} & 1 \\ & \vdots \\ 1 & \dots \end{array} \right), & \beta_2(5) &= \left( \begin{array}{c|c} & i \\ & \vdots \\ . & 1 \dots \end{array} \right), \\ \beta_3(5) &= \left( \begin{array}{c|c} & i \\ & \vdots \\ .. & 1 \dots \end{array} \right), & \beta_4(5) &= \left( \begin{array}{c|c} & \vdots \\ & -i \\ \dots & i \end{array} \right). \end{aligned} \right\} \tag{2.20}$$

For the symmetric case we may represent the  $\Gamma_s(\beta)$ ,  $\beta = 1, 2, \dots, 10$  by column matrices with zeros except a one at the  $\beta$ -th row, where  $E_k$  stands for  $\beta = 1, 2, 3$ ;  $H_k$  for  $\beta = 4, 5, 6$ ;  $\phi_\mu$  for  $\beta = 7, 8, 9, 10$ . The matrices obtained in this manner are identical with Kemmer's  $10 \times 10$  matrices (his equation (53)) provided all signs are reversed. They will not be reproduced here.

A complete classification of the spin functions is obtained from the  $\Gamma_a$  and  $\Gamma_s$  by multiplication with the four  $\Sigma(\Pi)$ . It will be seen that this would lead to  $\pi$ -mesons and light quanta only. To obtain  $K$ -mesons as well it is necessary to introduce further operators in  $(\Omega, \Omega')$  space (denoted as isospace). It is of course possible to introduce operators in this space corresponding to angular momenta different from Pauli type of spin. At present, however, it will be necessary to introduce a momentum  $I$  around the figure axis only—though in future it may well be required to introduce more general quantities. Let thus

$$I = -i \partial_\omega + \frac{1}{4} (\Pi_3 - \Pi'_3) = -i U^{-1} \partial_\omega U \tag{2.21}$$

which commutes with all  $\Pi_l, \Pi'_l$ . Here

$$\omega = \varphi - \varphi' \quad \text{i. e.} \quad \partial_\omega = \frac{1}{2} (\partial_\varphi - \partial_{\varphi'}) \tag{2.22}$$

and

$$U = e^{i \frac{\varphi}{2} \Pi_3} e^{i \frac{\varphi'}{2} \Pi'_3} = e^{i \frac{1}{4} \omega (\Pi_3 - \Pi'_3)} e^{i \frac{1}{4} (\varphi + \varphi') (\Pi_3 + \Pi'_3)} \tag{2.23}$$

Like the  $\Pi_l, \Pi'_l$  the operator  $I$  is invariant under rotation of the external frame.

In addition to the four functions  $\Sigma_\sigma(\Pi)$  we shall require four symmetric functions  $\kappa_\sigma$ ,

$$\kappa_l = \cos \omega \Sigma_l(\Pi), \quad \kappa_4 = -\sin \omega \Sigma_4(\Pi), \tag{2.24}$$

and four antisymmetric functions  $\nu_\sigma$ ,

$$\nu_l = -\sin \omega \Sigma_l(\Pi), \quad \nu_4 = \cos \omega \Sigma_4(\Pi). \tag{2.25}$$

The symmetry refers to interchange of dashed and undashed operators and coordinates so that  $\Sigma_l$  and  $\cos \omega$  are symmetric,  $\Sigma_4$  and  $\sin \omega$  anti-symmetric. It will be noted that

$$I^2 \Sigma_\sigma(\Pi) = 0, \quad I^2 \kappa_\sigma = \kappa_\sigma, \quad I^2 \nu_\sigma = \nu_\sigma. \tag{2.26}$$

Wave functions  $\Psi$  can now be written as a sum over spin functions each multiplied by a real space-time function. This reality condition will be found to be of considerable importance. Furthermore we postulate that only those spin functions which are antisymmetric under exchange of all pairs of dashed and undashed operators should be used. This leads to four types of wave functions  $\Psi_m, \Psi_\pi, \Psi_\kappa, \Psi_\nu$ . Here  $\Psi_m$  and  $\Psi_\pi$  are based on  $\Sigma_4(\Pi)$  and  $\Sigma_l(\Pi)$  respectively forming a  $\pi$ -singlet and triplet. From the postulate of antisymmetry then,  $\Psi_m$  depends on  $\Sigma_4(\Pi) \Gamma_s$ , and  $\Psi_\pi$  on  $\Sigma_k(\Pi) \Gamma_a$ , so that we can write

$$\Psi_m = \Sigma_4(\Pi) \left\{ \sum_{k=1}^3 (\Gamma_s(E_k) E_k(x_\mu) - \Gamma_s(H_k) H_k(x_\mu) + \Gamma_s(\phi_k) \phi_k(x_\mu)) - \Gamma_s(\phi_4) \phi_4(x_\mu) \right\} \tag{2.27}$$

and

$$\Psi_\pi = \sum_{l=1}^3 \sum_{\beta=1}^5 \Sigma_l(\Pi) \Gamma_a(\beta) \Phi_{l\beta}(x_\mu) \tag{2.28}$$

where the space-time functions  $E_k(x_\mu)$  etc.,  $\Phi_{l\beta}(x_\mu)$  are assumed to be real.

Two further wave functions  $\Psi_\kappa$  and  $\Psi_\nu$  can be formed from the  $\kappa_\sigma$  and  $\nu_\sigma$ , the former with the help of  $\Gamma_a$ , and the latter with  $\Gamma_s$ ,

$$\Psi_\kappa = \sum_{\sigma=1}^4 \sum_{\beta=1}^5 \kappa_\sigma \Gamma_a(\beta) X_{\sigma\beta}(x_\mu) \tag{2.29}$$

and

$$\Psi_\nu = \sum_{\sigma=1}^4 \sum_{\beta=1}^{10} \nu_\sigma \Gamma_s(\beta) V_{\sigma\beta}(x_\mu) \tag{2.30}$$

again with real functions  $X_{\sigma\beta}(x_\mu)$  and  $V_{\sigma\beta}(x_\mu)$ . We note with (2.26)

$$I^2 \Psi_m = 0, \quad I^2 \Psi_\pi = 0, \quad I^2 \Psi_\kappa = \Psi_\kappa, \quad I^2 \Psi_\nu = \Psi_\nu. \tag{2.31}$$

*Isobaric Spin and Charge Operators*

The various spin operators permit formulation of conservation laws from the wave equations (2.9) and (2.11). For this purpose let  $J_c$  be an operator independent of  $x_\mu$  which commutes with the  $B_\mu$  and with  $M$ . Then

$$\partial_\mu J_{c\mu} = 0 \quad \text{where} \quad J_{c\mu} = i \bar{\Psi} J_c B_\mu \Psi. \tag{2.32}$$

We shall also demand that  $J_c$  be symmetrical in all dashed and undashed operators. A total of sixteen such  $J_c$  operators exist which can be derived from the  $(\Pi_l + \Pi'_l) R_l$ , the  $I(\Pi_l - \Pi'_l) R_l$  or from their products. Since according to (2.31) eigenvalues  $I^2 = 0$  and  $I^2 = 1$  of  $I^2$  only are required it is possible to derive these sixteen  $J_c$  from three basic operators  $A_l$  (**A**)

$$A_l = \frac{1}{2} R_l (\mu \Pi_l + \mu' \Pi'_l) = \frac{1}{2} R_l \alpha_l \quad (\text{no sum}) \tag{2.33}$$

where

$$\left. \begin{aligned} \mu &= \frac{1 - I^2 + 2I}{1 + I^2}, & \mu' &= \frac{1 - I^2 - 2I}{1 + I^2} \\ \text{i. e. } \mu^2 &= \mu'^2 = 1; & \mu &= \mu' = 1 \text{ if } I = 0; & \mu &= I, \\ & & \mu' &= -I \text{ if } I^2 = 1. \end{aligned} \right\} \tag{2.34}$$

The  $R_l$  (2.13) are required here so that  $A_l$  commutes with  $B_\mu$ . From  $A_l$  we derive three operators  $Q_l$  (**Q**) by

$$i \mathbf{Q} = \mathbf{A} \times \mathbf{A}, \quad \text{i. e. } Q_l = \frac{1}{2} R_l (\Pi_l + \Pi'_l) = R_l q_l. \tag{2.35}$$

Besides these six operators  $A_l, Q_l$  ten further ones are obtained for  $J_c$  namely six  $E_{kl}$ , three  $A_{kl}$ , and  $J_c = 1$ . Here

$$E_{kl} = A_k A_l + A_l A_k - \delta_{kl} = \frac{1}{2} \mu \mu' R_k R_l (\Pi_k \Pi'_l + \Pi_l \Pi'_k), \tag{2.36}$$

and

$$\left. \begin{aligned} A_{kl} &= \frac{1}{2} (A_k Q_l - A_l Q_k + Q_l A_k - Q_k A_l) = \\ & \frac{1}{4} R_k R_l (\mu - \mu') (\Pi_k \Pi'_l - \Pi_l \Pi'_k) \end{aligned} \right\} \tag{2.37}$$

Introduction of these ten operators  $J_c(1, E_{kl}, A_{kl})$  into expression (2.32) for  $J_{c\mu}$  leads after integration over spin variables to antisymmetric expressions in the real space-time functions entering  $\Psi$ . These expressions vanish if the space-time functions commute. These ten  $J_c$  can, therefore, be used to formulate the reality conditions in an invariant manner. They are also expected to be of use for the formulation the commutation rules between these real space time functions (cf. § 5).

The remaining six  $J_c$  namely  $Q_l$  and  $A_l$  lead in a similar manner to symmetric expressions and can therefore be used for the formulation of the two main conservation laws, conservation of electric charge and of the third component of isobaric spin. We note in this connection that  $Q_3$  for instance commutes with  $A_3$ , but with none other of the six  $Q_l, A_l$ . From  $Q_l$  and  $A_l$  we define two vector operators  $\mathbf{T}$  and  $\mathbf{S}$  by

$$T_l = \frac{1}{2} (Q_l + A_l) = \frac{R_l}{1 + I^2} \left( \frac{\Pi_l + \Pi'_l}{2} + I \frac{\Pi_l - \Pi'_l}{2} \right) \quad (2.38)$$

and (use  $I^3 = I$  which holds for  $I^2 = 0, 1$ )

$$S_l = \frac{1}{2} (Q_l - A_l) = \frac{R_l I^2}{1 + I^2} \left( \frac{\Pi_l + \Pi'_l}{2} - I \frac{\Pi_l - \Pi'_l}{2} \right). \quad (2.39)$$

These operators as well as  $\mathbf{Q}$  satisfy the angular momentum relations

$$\mathbf{Q} \times \mathbf{Q} = i \mathbf{Q}, \quad \mathbf{T} \times \mathbf{T} = i \mathbf{T}, \quad \mathbf{S} \times \mathbf{S} = i \mathbf{S} \quad (2.40)$$

(provided  $I^2 = 0, 1$ ) though the generating operator  $\mathbf{A}$  does not do so. We shall interpret  $Q_3$  and  $\mathbf{T}$  as the operators for electric charge and isobaric spin.  $\mathbf{S}$  will be denoted as isospin shift because  $Q_3 = T_3 + S_3$ .  $S_3$  was originally introduced by HEISENBERG<sup>3)</sup> together with isobaric spin;  $2 S_3$  is the so called strangeness. In connection with these interpretations it will be remembered that the  $\Pi_l, \Pi'_l$ , and  $I$  are invariant under rotations of the external frame (in  $\Omega, \Omega'$  space) in a similar way in which the angular momenta of a spinning top, referred to its axes of symmetry are invariant under rotation. Since the first and second components,  $\Pi_1, \Pi_2$ , were connected with reflexions it seems natural to use the third one for the definition of charge. This, however, is no compelling reason. It will be shown in the discussion § 6, that a modification of the mass operator introduced below can be given such that the third components  $Q_3$  and  $T_3$  only are conserved (as well as  $T^2$ ).

Matrix representations of the  $J_c$  are frequently useful. For this purpose we note that the operators  $\alpha_l$  and  $q_l$  introduced in (2.33) and (2.35) are given by

$$\alpha_l = \alpha_l(4) = I \frac{\Pi_l - \Pi'_l}{2}, \quad \text{if } I^2 = 1 \quad (2.41)$$

and

$$\alpha_l = \alpha_l(3 + 1) = \frac{\Pi_l + \Pi'_l}{2} = q_l = q_l(4) = q_l(3 + 1), \quad \text{if } I^2 = 0 \quad (2.42)$$

Here  $\alpha_l(4)$  denotes a  $4 \times 4$  matrix;  $\alpha_l(3 + 1)$  indicates a  $4 \times 4$  matrix which can be decomposed into a  $3 \times 3$  and a  $1 \times 1$  matrix. The actual form of these matrices is obtained by representing the functions  $\Sigma_\sigma(\Pi)$  (referring to  $I^2 = 0$ )  $\kappa_\sigma$  and  $\nu_\sigma$  (referring to  $I^2 = 1$ ) by four sets of column matrices with zeros in every row except the  $\sigma - t h$  which contains a 1. We then find

$$\alpha_1(4) = \left( \begin{array}{ccc|c} & & & -i \\ & & & \cdot \\ & & & \cdot \\ i & \cdot & \cdot & \cdot \end{array} \right), \quad \alpha_2(4) = \left( \begin{array}{ccc|c} & & & \cdot \\ & & & -i \\ & & & \cdot \\ \cdot & i & \cdot & \cdot \end{array} \right), \quad \alpha_3(4) = \left( \begin{array}{ccc|c} & & & \cdot \\ & & & \cdot \\ & & & -i \\ \cdot & \cdot & i & \cdot \end{array} \right), \quad (2.43)$$

and

$$\left. \begin{aligned} \alpha_1(3 + 1) = q_1(4) &= \left( \begin{array}{ccc|c} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & -i & \cdot \\ \cdot & i & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{array} \right), \\ &= q_1(3 + 1) \\ q_2(4) &= \left( \begin{array}{ccc|c} \cdot & \cdot & i & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ -i & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{array} \right), & q_3(4) &= \left( \begin{array}{ccc|c} \cdot & -i & \cdot & \cdot \\ i & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{array} \right). \end{aligned} \right\} (2.44)$$

The decomposition of  $\alpha_l(3 + 1) = q_l(3 + 1) = q_l(4)$  is indicated by rimming.

It seems of interest to mention here that  $\alpha_l(4)$  and  $\alpha_l(3) = q_l(3)$  are a four and a three dimensional representation of an  $\alpha$ -algebra, based on three generating elements  $\alpha_l$  satisfying the same rules (2.4) as do the four  $\beta_\mu$ . This algebra has a further three dimensional representation by  $\alpha_l(3^-) = -q_l(3)$ , and a one dimensional one,  $\alpha_l(1) = (\cdot)$ .

*Mass Operator.* From Kemmer's investigations it follows that the  $\beta_\mu(5)$  connected with antisymmetric spin functions  $\Gamma_a$  occurring in  $\Psi_\pi$  and  $\Psi_\kappa$  lead to particles with mechanical spin 0, while the  $\beta_\mu(10)$  connected with  $\Gamma_s$  lead to spin 1 particles. An operator  $M$  can be designed such that its eigenvalue differs for the four wave functions (2.27)–(2.30) while it commutes with  $Q_3, T_3, T^2$ , and  $I^2$ . This does not completely determine the forms of  $M$ . An ad hoc definition is, therefore, proposed which will be seen to yield a correct mass ratio for  $\pi$ - and  $K$ -mesons:

$$M = M(\Pi) + M(\rho, \sigma) \quad (2.45)$$

where ( $C$  and  $c$  are numerical constants)

$$M(\Pi) = C (1 + I^2)^2 (T^2 + I^2) \quad (2.46)$$

and

$$M(\varrho, \sigma) = c \left( \frac{\varrho_3 + \varrho'_3}{2} \right)^2 \sum_{k=1}^3 \left( \frac{\sigma_k + \sigma'_k}{2} \right)^2. \tag{2.47}$$

We note that  $M(\varrho, \sigma) \Gamma_a = 0$ .

The form of  $M(\Pi)$  is such that in a simple manner it separates eigenvalues corresponding to different values of  $T^2$  and  $I^2$ .  $M(\varrho, \sigma)$  will be required to obtain the Maxwell equations. Clearly a number of other possibilities for  $M$  do exist. A particular modification leading to conservation of the third components  $Q_3, T_3$  only and not of  $Q_1, Q_2, T_1, T_2$  would be obtained by multiplication of (2.45) by  $\Pi_3 \Pi'_3$ , cf. § 6.

### 3. Solutions

We shall now introduce the four wave functions (2.27)–(2.30) into the wave equation (2.9) using  $M$  from (2.45)–(2.47). In each case a number of wave equations for the real space time functions will be found after multiplication with appropriate spin functions and integration over the spin variables. The procedure can be simplified, however, by using matrix representations appropriate for the spin functions involved in the particular case.

*Maxwell field  $\Psi_m$ .* The wave function  $\Psi_m$ , (2.27) is proportional to  $\Sigma_4(\Pi)$ . Hence with (2.31), (2.46), (2.35) and (2.38)

$$I \Psi_m = 0, \quad M(\Pi) \Psi_m = 0, \quad Q_l \Psi_m = 0, \quad T_l \Psi_m = 0 \tag{3.1}$$

and with (2.47)

$$\left. \begin{aligned} M(\varrho, \sigma) \Gamma_s(E_k) = 2 c \Gamma_s(E_k), \quad M(\varrho, \sigma) \Gamma_s(H_k) = 2 c \Gamma_s(H_k), \\ M(\varrho\sigma) \Gamma_s(\phi_\mu) = 0. \end{aligned} \right\} \tag{3.2}$$

Thus,  $\Psi_m$  has one  $\Pi$ -component describing an isobaric spin singlet, and ten  $(\varrho, \sigma)$  components. Action of the  $\beta_\mu$  on the  $\Gamma_s$  may be represented in terms of  $\beta_\mu(10)$  and the ten resulting space time equations are identical with the Maxwell equations in the form

$$\left. \begin{aligned} \text{grad } \phi_4(x_\mu) + \partial_0 \phi(x_\mu) + 2 c E(x_\mu) = 0, \\ \text{curl } \phi(x_\mu) - 2 c H(x_\mu) = 0, \quad \text{curl } H(x_\mu) - \partial_0 E(x_\mu) = 0, \\ - \text{div } E(x_\mu) = 0. \end{aligned} \right\} \tag{3.3}$$

The mass constant  $c$  thus simply gives a measure for the vector potential  $\phi_\mu(x_\mu)$ .

*$\pi$ -Mesons,  $\Psi_\pi$ .* For the wave function  $\Psi_\pi$  (2.28) depending on  $\Sigma_l(\Pi)$  clearly

$$I \Psi_\pi = 0, \quad M(\pi) \Psi_\pi = 2 C \Psi_\pi, \quad M(\varrho, \sigma) \Psi_\pi = 0. \tag{3.4}$$

It represents an isobaric spin triplet where using (2.35), (2.38) and (2.42)

$$Q_l = T_l = R_l q_l(3). \tag{3.5}$$

Here  $q_l(3)$  is the  $3 \times 3$  rimmed sub matrix of  $q_l(3 + 1)$  in (2.44), and this matrix acts on the suffix  $l$  of the real space time functions  $\Phi_{l\beta}(x_\mu)$ . Since  $\Psi_\pi$  depends on the  $\Gamma_a$ , the  $\beta_\mu$  according to (2.20) can be represented by matrices  $\beta_\mu(5)$  acting on the suffix  $\beta$  of  $\Phi_{l\beta}$ . Action of the  $\Pi_1 \Pi'_1$  and  $\Pi_2 \Pi'_2$  which enter the wave equation by (2.10) can be obtained from table 1. Thus if we introduce matrices  $\varepsilon_{kk}(4) = \varepsilon_{kk}(3 + 1)$  by

$$\left. \begin{aligned} \varepsilon_{11}(4) = \varepsilon_{11}(3 + 1) &= \left( \begin{array}{c|c} 1 & \\ \hline -1 & \\ -1 & \\ \hline & 1 \end{array} \right), & \varepsilon_{22}(4) = \varepsilon_{22}(3 + 1) &= \left( \begin{array}{c|c} -1 & \\ \hline 1 & \\ -1 & \\ \hline & 1 \end{array} \right), \\ \varepsilon_{33}(4) = \varepsilon_{33}(3 + 1) &= \left( \begin{array}{c|c} -1 & \\ \hline -1 & \\ 1 & \\ \hline & 1 \end{array} \right) \end{aligned} \right\} \tag{3.6}$$

and if we understand by  $\varepsilon_{kk}(3)$  the rimmed  $3 \times 3$  sub-matrices, then the wave equation becomes after integration over spin variables

$$\varepsilon_{11}(3) \beta_k(5) \partial_k + \varepsilon_{22}(3) \beta_4(5) \partial_4 - 2 C, \quad \Phi(x_\mu) = 0 \tag{3.7}$$

where  $\Phi(x_\mu)$  represents the  $\Phi_{l\beta}(x_\mu)$  with the  $\varepsilon_{kk}$  acting on the three suffixes  $l$  and the  $\beta_\mu(5)$  on the five suffixes  $\beta$ . From Kemmer's investigations it is known that the  $\beta_\mu(5)$  described particles with zero mechanical spin; equation (3.7) contains three such particles, with eigenvalues of  $Q_3 = T_3$  obtained by diagonalising  $q_3(3)$  i.e.  $(1, 0, -1)$ . Clearly (3.7) describes  $\pi$ -mesons provided the constant  $C$  is chosen appropriately.

*K-Mesons,  $\Psi_\kappa$ .* The wave function  $\Psi_\kappa$ , (2.29), depends on the four  $\kappa_\sigma$ , so that with (2.31), (2.46) and (2.47)

$$I^2 \Psi_\kappa = \Psi_\kappa, \quad M(\Pi) \Psi_\kappa = 7 C \Psi_\kappa, \quad M(\rho, \sigma) \Psi_\kappa = 0. \tag{3.8}$$

It represents two isobaric spin doublets with (use (2.35), (2.38), (2.39), (2.41) and (2.42)),

$$\left. \begin{aligned} Q_l \Psi_\kappa &= R_l q_l(4) \Psi_\kappa, & T_l \Psi_\kappa &= \frac{1}{2} R_l (q_l(4) + \alpha_l(4)) \Psi_\kappa, \\ S_l \Psi_\kappa &= \frac{1}{2} R_l (q_l(4) - \alpha_l(4)) \Psi_\kappa. \end{aligned} \right\} \tag{3.9}$$

Since  $\Psi_\kappa$  depends on the  $\Gamma_a$  the  $\beta_\mu$  can be represented by the  $\beta_\mu(5)$  and the wave equation becomes

$$\varepsilon_{11}(4) \beta_\kappa(5) \partial_\kappa + \varepsilon_{22}(4) \beta_4(5) \partial_4 - 7 C, \quad X = 0 \tag{3.10}$$

where  $X$  represents the functions  $X_{\sigma, \beta}(x_\mu)$  with the  $\varepsilon_{kk}(4)$ ,  $\alpha_i(4)$ ,  $q_l(4)$  acting on the four suffixes  $\sigma$ , and the  $\beta_\mu(5)$  on the five suffixes  $\beta$ . This equation thus describes four particles with zero mechanical spin. They have electric charge  $(1, 0, -1, 0)$  and 3rd isobaric spin components  $(1/2, -1/2, -1/2, 1/2)$  as is seen by diagonalising  $q_3(4)$  and  $\alpha_3(4)$  and using (3.9). Equation (3.10) thus described  $K$ -mesons with mass  $7 C$ . Its ratio  $7 : 2$  to the  $\pi$ -meson mass is in close agreement with the experimental value  $966 : 273$  for charged  $K$ - and  $\pi$ -mesons.

$\nu$ -Mesons,  $\Psi_\nu$ . This case based on the wave function  $\Psi_\nu$  (2.30), again leads to two isobaric spin doublets with the same charge and isobaric spin properties as  $K$ -mesons. The antisymmetry of the four  $\nu_\sigma$ , however, entails the use of  $\Gamma_s$  instead of  $\Gamma_a$ , and hence of a description of the  $\beta_\mu$  by  $\beta_\mu(10)$ . This wave function therefore describes particles with mechanical spin 1, by

$$\varepsilon_{11}(4) \beta_\kappa(10) \partial_\kappa + \varepsilon_{22}(4) \beta_4(10) \partial_4 - (7 C + 2 c\nu), \quad V = 0. \quad (3.11)$$

Here  $V$  represents the functions  $V_{\sigma, \beta}(x_\mu)$  with the  $\varepsilon_{kk}(4)$ ,  $q_l(4)$  and  $\alpha_i(4)$  acting on the four suffixes  $\sigma$  and the  $\beta_\mu(10)$  acting on the ten suffixes  $\beta$ .  $\nu$  is a diagonal  $10 \times 10$  matrix acting on  $\beta$  with 1 in the first six, 0 in the following four diagonal positions (cf. 3.2). Formation of the second order (in  $\partial_\mu$ ) equations shows that this particle has a mass

$$M_\nu = (7 C (7 C + 2 c))^{\frac{1}{2}}. \quad (3.12)$$

To derive this expression in a formal way from (3.11) it must be noticed that the  $\beta_\mu(10)$  do not commute with the matrix  $\nu$ , but as can be seen from the matrix representation

$$\beta_\mu(10) \nu + \nu \beta_\mu(10) = \beta_\mu(10). \quad (3.13)$$

Thus, it has been shown that the wave equation (2.9) together with the postulate of 'spin' antisymmetry leads to the Maxwell equations (3.3) and to the wave equations (3.7) and (3.10) for  $\pi$ - and  $K$ -mesons respectively, together with the correct isobaric spin assignments. It also leads to a  $\nu$ -meson which has unit mechanical spin, equal isobaric properties with the  $K$ -mesons, but a different mass.

*Energy Momentum Tensor.* The  $B_\mu$  entering wave equation (2.9) satisfy the same algebraic rules (2.4) as do the  $\beta_\mu$ . A symmetric energy momentum tensor  $\Theta_{\mu\nu}$  can, therefore, be derived in the same manner as done by KEMMER provided it is observed that  $M$  is now an operator. Thus generalising from Kemmer's equation (19) we have (the commutator of  $M(\rho, \sigma)$  and  $B_\mu B_\nu$  applied to  $\Psi$  vanishes)

$$\Theta_{\mu\nu} = \bar{\Psi} M (B_\mu B_\nu + B_\nu B_\mu) \Psi - \delta_{\mu\nu} \bar{\Psi} M \Psi. \quad (3.14)$$



In particular, since  $\Pi_1 \Pi_1' \Pi_2 \Pi_2' = -\Pi_3 \Pi_3'$ ,

$$\Theta_{4\kappa} = -\bar{\Psi} M \Pi_3 \Pi_3' (\beta_4 \beta_\kappa + \beta_\kappa \beta_4) \Psi \quad (3.15)$$

and using  $2 B_4^2 - 1 = -R_2$ ,  $R_2^2 = 1$  and the definition (2.12) of  $\bar{\Psi}$ ,

$$\Theta_{44} = -\Psi^+ M \Psi. \quad (3.16)$$

For each of the fields discussed above this leads to the well known expressions, e. g.

$$\Theta_{44} = -2c (E^2(x_\mu) + H^2(x_\mu)) \quad (3.17)$$

for the Maxwell case,

$$\Theta_{44} = -2C \sum_{l=1}^3 \sum_{\beta=1}^5 \Phi_{l\beta}^2(x_\mu) \quad (3.18)$$

for  $\pi$ -mesons, etc.

If we demand that the energy density  $-\Theta_{44}$  be positive then both  $C$  and  $c$  must be positive. If furthermore  $C = c$  then  $M_\nu \simeq 1100$  electron masses would follow.

#### 4. Reflexions

In the discussion of § 1 we have demanded that reflexions other than coordinate replacements should be expressed as continuous transformations. This led to the introduction of the  $\Pi_i(\Omega)$ ,  $\Pi_i'(\Omega')$  in the new  $(\Omega, \Omega')$  angular space (isospace). As a consequence through the factors  $\Pi_1 \Pi_1'$  and  $\Pi_2 \Pi_2'$  the wave equation (2.9) has four components for each one in the previous treatments. This wave equation contains automatically the reflected ones expressed by appropriate changes in the angles  $\Omega$  or  $\Omega'$ . Thus, as can be seen from (1.11) and (1.10), replacement of  $\Omega = (\theta, \chi, \varphi)$  by  $\Omega_1 = (\pi - \theta, \chi - \pi, \pi - \varphi)$  (leaving  $\Omega'$  unaltered) replaces  $\Pi_1(\Omega) \Pi_1'(\Omega')$  by  $\Pi_1(\Omega_1) \Pi_1'(\Omega') = -\Pi_1(\Omega) \Pi_1'(\Omega')$  leaving  $\Pi_2 \Pi_2'$  unaltered. It is therefore equivalent to replacing  $x_k$  by  $-x_k$ . Thus the wave equation remains invariant if simultaneously we replace  $x_k$  by  $-x_k$  and  $\Omega$  by  $\Omega_1$  provided  $\Psi(x_k, \Omega)$  is also replaced by  $\Psi(-x_k, \Omega_1)$  and if similar replacements are made in all definitions of charge, isobaric spin and other operators. We remember that transformations of the angles  $\Omega, \Omega'$  are equivalent to unitary transformations. The above case for example, is equivalent to unitary transformation by  $\Pi_2$  for  $\Pi_2(\Pi_1 \Pi_1') \Pi_2 = -\Pi_1 \Pi_1'$ . Similar transformations can be made in connection with reflexion of  $x_4$  or of all four  $x_\mu$ . Transformations of this kind will be denoted as insignificant transformations. They demonstrate that the choice of the original frame  $(x_k, x_0)$  is arbitrary. We might as well have chosen  $(-x_k, x_0)$ . Quite a number of other arbitrary choices have been made, of

course. One, for instance, is the choice of  $+i$  in (1.1) which might have been replaced by  $-i$ . The choice between these two is equivalent to the choice of a right handed or a left handed  $\Pi_l$  system. Another arbitrary choice concerns the choice  $+i$  in the definition of  $\mathbf{Q}$  in (2.35). Insignificant transformations can always be derived such as to put into evidence that a certain choice of a coordinate frame may be replaced by another.

*Significant Transformations.* In contrast, significant transformations make statements concerning different physical states. As an example we consider charge conjugation. We consider the replacement  $\Omega \rightarrow \Omega_1$  discussed above, or its equivalent, unitary transformation by  $\Pi_2$ , and supplement it by the unitary transformation by  $\Pi'_2$ , i. e. we are interested in simultaneous replacements  $\Omega \rightarrow \Omega_1, \Omega' \rightarrow \Omega'_1$  or in the equivalent unitary transformation by

$$C_2 = \Pi_2 \Pi'_2 = C_2^{-1}. \tag{4.1}$$

Since both  $\Pi_2$  and  $\Pi'_2$  are equivalent to replacing in the wave equation  $x_k$  by  $-x_k$ ,  $C_2$  leaves the wave equation invariant, but it transforms  $\Psi$  into

$$\Psi_c(x_k, \Omega, \Omega') = C_2 \Psi(x_k, \Omega, \Omega'). \tag{4.2}$$

If now we were to replace in all definitions the  $\Pi_l, \Pi'_l$  by the transformed ones, e. g.

$$Q_3 \rightarrow Q_{3c} = C_2 R_2 \frac{\Pi_3 + \Pi'_3}{2} C_2^{-1} = -Q_3 \tag{4.3}$$

then complete invariance would be obtained, e. g.

$$J_\mu = \bar{\Psi} Q_3 B_\mu \Psi = \bar{\Psi}_c Q_{3c} B_\mu \Psi_c \tag{4.4}$$

and the transformation would be an insignificant one. To obtain a significant transformation we shall not transform the various definitions (4.3), etc., but make use of the fact that together with a certain  $\Psi(x_\mu)$ , another wave function,  $\Psi_c(x_\mu)$  also solves the same wave equation. This  $\Psi_c$  then leads to a different physical state, namely one in which all electric charges are reserved, because

$$\bar{\Psi}_c Q_3 B_\mu \Psi_c = \bar{\Psi} (C_2 Q_3 C_2) B_\mu \Psi = -\bar{\Psi} Q_3 B_\mu \Psi \tag{4.5}$$

The physical significance of  $C_2$  is that to each wave function  $\Psi$  describing certain types of particles another one  $\Psi_c$  is coordinated in which all electric charges and currents are reversed.

Charge conjugation can be considered as a special case of a number of continuous transformations like charge rotation

$$C_2(\vartheta) = e^{i\vartheta} e^{i\vartheta Q_2} = e^{i\vartheta} (1 + Q_2^2 (\cos \vartheta - 1) + i Q_2 \sin \vartheta) \tag{4.6}$$

where  $\vartheta$  is a parameter;  $C_2 = C_2(\pi)$ . This transformation too leaves the wave equation invariant; it rotates the vector operator  $\mathbf{Q}$  by an angle  $\vartheta$

around the  $Q_2$  axis. In view of definition (2.35) of  $\mathbf{Q}$  this transformation involves not only the  $\Pi_l, \Pi'_l$  but also  $R_2$ , except when  $\vartheta = \pi$ . Another continuous transformation which leaves the wave equation invariant and contains  $C_2$  as a special case is by

$$D_2(\vartheta) = e^{i\vartheta\Pi_2\Pi'_2}; \quad D_2\left(\frac{\pi}{2}\right) = i C_2. \quad (4.7)$$

*Internal Parity Reflexion.* This reflexion can be defined as a significant transformation which leaves the (mechanical) spin operator  $1/2(\sigma_k + \sigma'_k)$  invariant but reverses the energy flux  $\theta_{4k}$  without affecting the charge. Clearly unitary transformation by  $R_2 = -\varrho_2 \varrho'_2$  serves the purpose as may be seen from (3.15) and (2.5). The transformation of the wave function

$$R_2 \Psi = -\varrho_2 \varrho'_2 \Psi \quad (4.8)$$

affects the spin functions  $\Sigma_\sigma(\varrho)$  only in a manner shown in table 1. It is, therefore, equivalent to multiplying the various space time functions entering  $\Psi$  by  $+1$  or  $-1$ . Table 2 shows this change of sign for the Maxwell and the  $\pi$ -meson functions obtained with the help of (2.27), (2.28), (2.18) and (2.19).

Table 2

	$E_k$	$H_k$	$\phi_k$	$\phi_4$	$\Phi_{l_k}$	$\Phi_{l_4}$	$\Phi_{l_5}$
$R_2$	-	+	-	+	+	-	-

The result is identical with the well known parity assignments.

The above definition of internal parity reflexion loses its significance for particles without mechanical spin; yet a significance is usually attached to the internal parity of say  $\pi$ -mesons though this exhibits itself only when their interaction with nucleons is considered. I feel that one should conclude from this that boson fields contain internal variables which so far have not yet been recognised. In terms of these variables internal parity reflexion should describe the turning inside-out of a bosons as a continuous transformation. As a formal step in this direction we might assume that the Pauli matrices  $\varrho_k, \varrho'_k$  and  $\sigma_k, \sigma'_k$  entering by (2.5) the wave equation (2.9) have a physical meaning such that any representation can be chosen for them which is derived from (1.7) by unitary transformations. As in the case of the  $\Pi_l, \Pi'_l$  this involves angular spaces. For the  $\sigma_k, \sigma'_k$  the requirement is to some extent already satisfied by the form of the wave equation, containing them as  $(\boldsymbol{\sigma} \boldsymbol{d})$  and  $(\boldsymbol{\sigma}' \boldsymbol{d})$  only. A simultaneous unitary transformation of  $\boldsymbol{\sigma}$  and  $\boldsymbol{\sigma}'$  then is equivalent to a rotation of the ordinary  $x_k$ -frame; the angular coordinates connected with the  $\boldsymbol{\sigma}$  are thus the angles in ordinary space. For the  $\varrho_k, \varrho'_k$  however, the requirement is not obviously satisfied because Lorentz transformations

lead to a specific kind of unimodular transformation which do not include our requirements. The simplest possible extension of the definition of the  $\varrho_k$  which would permit internal parity reflexion could be obtained by defining similar to (1.10),

$$\varrho_l = (\mathbf{a}(\varrho) \mathbf{w}_l), \quad \varrho'_l = (\mathbf{a}'(\varrho) \mathbf{w}_l) \quad (4.9)$$

where  $\mathbf{a}(\varrho)$ ,  $\mathbf{a}'(\varrho)$  are Pauli matrices of the form (1.7), and  $\mathbf{w}_l$  are three orthogonal unit vectors defined in terms of certain Eulerian angles. For our purpose we may choose in particular  $\mathbf{w}_2$  such that

$$\varrho_2 = a_2(\varrho), \quad \varrho'_2 = a'_2(\varrho) \quad (4.10)$$

which implies that  $\varrho_1$  and  $\varrho_3$  do not contain  $a_2$ . We may then define

$$R_2(\vartheta) = e^{i\vartheta \frac{\varrho_2 + \varrho'_2}{2}} = 1 + \left( \frac{\varrho_2 + \varrho'_2}{2} \right)^2 (\cos \vartheta - 1) + \left. \begin{aligned} &+ i \frac{\varrho_2 + \varrho'_2}{2} \sin \vartheta \end{aligned} \right\} \quad (4.11)$$

so that

$$R_2 = R_2(\pi) = -\varrho_2 \varrho'_2 \quad (4.12)$$

and

$$R_2\left(\frac{\pi}{2}\right) = \frac{1 - \varrho_2 \varrho'_2}{2} + i \frac{\varrho_2 + \varrho'_2}{2}. \quad (4.13)$$

Transformation by  $R_2(\vartheta)$  does not leave the wave equation invariant; invariance is obtained, however, by a simultaneous rotation of the  $\mathbf{w}_l$  around the  $\mathbf{w}_2$  axis. Rotation by  $180^\circ$  then becomes equivalent to a replacement of  $\partial_k$  by  $-\partial_k$  in a manner similar to the example discussed in § 1. The turning inside out process in the Maxwell case for instance leaves  $H_k$  and  $\phi_4$  unaltered, while  $E_k$  and  $\phi_k$  are rotated such that for  $\vartheta = 90^\circ$ ,  $E_k \rightarrow \phi_k$ ,  $\phi_k \rightarrow -E_k$  and for  $\vartheta = 180^\circ$ ,  $E_k \rightarrow -E_k$ ,  $\phi_k \rightarrow -\phi_k$ . It would be desirable to go closer into this process than has been possible by the present formal description.

Finally transformation by

$$P(\vartheta) = e^{i\frac{\vartheta}{2}(\varrho_2 \Pi_2 + \varrho'_2 \Pi'_2)} = 1 + \left( \frac{\varrho_2 \Pi_2 + \varrho'_2 \Pi'_2}{2} \right)^2 (\cos \vartheta - 1) + \left. \begin{aligned} &+ i \left( \frac{\varrho_2 \Pi_2 + \varrho'_2 \Pi'_2}{2} \right) \sin \vartheta \end{aligned} \right\} \quad (4.14)$$

should be mentioned. It leaves the wave equation invariant, and for  $\vartheta = 180^\circ$  becomes

$$P(\pi) = -\varrho_2 \varrho'_2 \Pi_2 \Pi'_2 = R_2 C_2 \quad (4.15)$$

i. e. combined charge and internal parity transformation.

### 5. Reality Conditions and Quantisation

The space time functions entering the wave functions in (2.27)–(2.30) were all assumed real. This statement is not invariant under unitary transformations and it was mentioned in § 2 that an invariant formulation is possible in terms of vanishing currents,

$$\overline{\Psi}(x) J_{kl} B_{\mu} \Psi(x) = 0 \quad (5.1)$$

where the  $J_{kl}$  represents the ten operators (cf. (2.36, 2.37))

$$J_{kl} = E_{kl}, \quad A_{kl}, \quad 1. \quad (5.2)$$

In (5.1) integration over all spin variables is assumed to be carried out so that these expressions depend on  $x_{\mu}$  only. Conditions (5.1) remain valid if  $\Psi$  is multiplied by a phase factor  $\exp(i \vartheta Q_s)$  or  $\exp(i \vartheta A_s)$  because transformation of any of the  $J_{kl}$  by these terms (e.g.  $\exp(-i \vartheta Q_s) J_{kl} \exp(i \vartheta Q_s)$ ) leads to a linear combination of the ten  $J_{kl}$ .

The quantisation of the space time functions contained in  $\Psi$  is closely connected with the reality conditions. To demonstrate this we consider first a wave function of a neutral spin zero particle,

$$\beta_k(5) \partial_k + \beta_4(5) \partial_4 + \kappa, \quad \psi(x) = 0. \quad (5.3)$$

Here  $\psi(x)$  has five real components  $\psi_{\beta}(x)$  which satisfy (use 2.20)

$$\left. \begin{aligned} \partial_k \psi_5 + \kappa \psi_k &= 0, & -i \partial_4 \psi_5 + \kappa \psi_4 &= 0, \\ \partial_k \psi_k + i \partial_4 \psi_4 + \kappa \psi_5 &= 0. \end{aligned} \right\} \quad (5.4)$$

Now if  $\overline{\psi}(x) = \psi^+(x) (1 - 2\beta_4^2)$ , then  $\overline{\psi}(x) \beta_{\mu}(5) \psi(x)$  is conserved. From (5.3) and (5.4) we then find

$$\left. \begin{aligned} \kappa (\overline{\psi}(x') \beta_{\mu}(5) \psi(x) + \overline{\psi}(x) \beta_{\mu}(5) \psi(x')) &= \\ = (\partial_{\mu} - \partial'_{\mu}) (\psi_5(x') \psi_5(x) - \psi_5(x) \psi_5(x')) &. \end{aligned} \right\} \quad (5.5)$$

For classical fields this expression vanishes. When  $\psi_5(x')$  and  $\psi_5(x)$  do not commute, however, then it vanishes only if  $x = x'$ . Conversely the condition that the left hand side of (5.5) should vanish for  $x = x'$  requires that all  $\psi_{\beta}$  be real apart from a common phase factor.

Now quantization of a real field  $\psi_5(x)$  requires (cf. PAULI<sup>4</sup>) eqns. (32) and (22))

$$\psi_5(x') \psi_5(x) - \psi_5(x) \psi_5(x') = [\psi_5(x'), \psi_5(x)] = i D(x - x', \kappa) \quad (5.6)$$

where  $D(x - x', \kappa)$  represents the universal  $D$  function for rest mass  $\kappa$ . Hence the condition

$$\kappa (\overline{\psi}(x') \beta_{\mu}(5) \psi(x) + \overline{\psi}(x) \beta_{\mu}(5) \psi(x')) = i (\partial'_{\mu} - \partial_{\mu}) D(x - x', \kappa) \quad (5.7)$$

expresses the reality as well as the quantization condition.

Complete quantisation of the wave function  $\Psi$  involves not only the space time coordinates  $x_\mu$  but also the new angular coordinates. At present quantization of the space-time functions only will be considered, and consequently the four fields (2.27)–(2.30) will be treated separately. Let  $\Psi_f(x)$  be one of these four fields ( $f = m, \pi, \kappa, \nu$ ) and let  $M_f$  be the respective eigenvalue of the mass operator, defined as the value entering the second order wave equation

$$\square \Psi_f - M_f^2 \Psi_f = 0 \tag{5.8}$$

i.e. (for  $f = m$ , (5.8) holds for  $E(x_\mu)$  and  $H(x_\mu)$  only)

$$M_m = 0, \quad M_\pi = 2 C, \quad M_\kappa = 7 C, \quad M_\nu = (7 C (7 C + 2 c))^2. \tag{5.9}$$

We can then tentatively generalise (5.7) to

$$\left. \begin{aligned} \overline{\Psi}_f(x') \frac{1}{2} (M B_\mu + B_\mu M) J_{kl} \Psi_f(x) + \overline{\Psi}_f(x) \frac{1}{2} (M B_\mu + \\ + B_\mu M) J_{kl} \Psi_f(x') = i \delta_{kl} (\partial_\mu - \partial'_\mu) D(x - x', M_f). \end{aligned} \right\} \tag{5.10}$$

Integration over all spin variables on the left hand side is assumed. It will be remembered that  $J_{kl}$  commutes with both  $M$  and  $B_\mu$ . Also (cf. (2.46, 2.47))  $M(\Pi)$  commutes with  $B_\mu$ , but  $M(\varrho, \sigma)$  does not do so in the case of particles with mechanical spin 1, as indicated in (3.13). The case  $k = l$  is assumed to comprise for  $J_{kk}$  not only the three operators  $E_{kk}$ , but also the unity operator 1. In a matrix representation, the three  $E_{kk}$  are given as diagonal matrices (3.6). Together with 1 they can be combined into four matrices containing zeros except for a single diagonal element each. For spin 0 particles ( $f = \pi$  or  $K$ ) the four ( $f = K$ ) or three ( $f = \pi$ ) conditions arising from (5.10) with  $k = l$  are then identical with (5.7) for each of the four (three)  $\Pi$ -components, apart from signs. The remaining conditions (5.10),  $k \neq l$ , show that different  $\Pi$ -components commute.

The case of spin 1 particles will be illustrated on the Maxwell field  $\Psi_m$ . This field has a single  $\Pi$ -component  $\Sigma_4(\Pi)$ . All  $J_{kl}$  conditions then either give  $0 = 0$  (if  $k \neq l$ ) or they become identical with  $J_{kk} = 1$ . Using (3.13) thus

$$\left. \begin{aligned} -c (\overline{\Psi}_m(x') \beta_\mu(10) \Psi_m(x) + \overline{\Psi}_m(x) \beta_\mu(10) \Psi_m(x')) = \\ = i (\partial_\mu - \partial'_\mu) D(x - x', 0). \end{aligned} \right\} \tag{5.11}$$

Inserting for  $\Psi_m$  from (2.27) yields for  $\mu = 1, 2, 3$ ,

$$\left. \begin{aligned} -c ([E_1(x'), \phi_4(x)] + [E_1(x), \phi_4(x')] - [H_2(x'), \phi_3(x)] - \\ - [H_2(x), \phi_3(x')] + [H_3(x'), \phi_2(x)] + [H_3(x), \phi_2(x')]) = \\ = i (\partial_1 - \partial'_1) D(x - x', 0); \quad \text{cycl.} \end{aligned} \right\} \tag{5.12}$$

and for  $\mu = 4$

$$\left. \begin{aligned} -i c \sum_{k=1}^3 ([E_k(x'), \phi_k(x)] + [E_k(x), \phi_k(x')]) &= \\ &= i (\partial_4 - \partial'_4) D(x - x', 0). \end{aligned} \right\} (5.13)$$

Expressing  $E_k$  and  $H_k$  by  $\phi_\mu$  through the field equations (3.3) leads to four conditions containing the  $\phi_\mu$  and their derivatives only. They can be fulfilled if

$$[\phi_\mu(x'), \phi_\nu(x)] = -\frac{2}{3} i D(x - x', 0) \delta_{\mu\nu} \quad (5.14)$$

with

$$\delta_{\mu\nu} = 0 \text{ if } \mu \neq \nu; \quad \delta_{kk} = 1 \text{ if } k = 1, 2, 3; \quad \delta_{44} = -1. \quad (5.15)$$

Further investigation will have to show whether (5.14) is the only conclusion that can be drawn from (5.13) and whether (5.10) requires modification.

## 6. Discussion

The developments described in this paper are based on a criticism of the usual methods of dealing with reflexions. Arising from this it was postulated that all reflexions except coordinate replacements should be treated as continuous transformations. This required the replacements of four-vectors by operators according to (1.1) and led to the introduction of a new angular space (isospace). The application of these ideas to bosons is based on the identity (2.1) and is dominated by a very important difference between classical and quantum mechanics. In classical relativistic theory the momentum four-vector  $p_\mu$  is connected to the velocity four-vector  $v_\mu$  through the rest mass  $\kappa$  by  $p_\mu = \kappa v_\mu$ ; in quantum mechanics the two are defined independently (cf. (2.2), (2.3)). The quantum mechanical definition of  $v_\mu$  is, of course, closely correlated with Schrödingers Zitterbewegung which exists not only in the Dirac equation but also for bosons (it is longitudinal for spin zero bosons). The independence of definition of the  $p_\mu$  and  $v_\mu$  four-vectors has a profound influence on the wave equation when the replacements (2.6), (2.7) are made, replacing  $p_k v_k$  by  $\Pi_1 \Pi'_1 p_k v_k$ , and  $p_0 v_0$  by  $-(i \Pi_2) (i \Pi'_2) p_0 v_0$ . For clearly the  $\Pi_l, \Pi'_l$  occur only as products  $\Pi_l \Pi'_l$ . Now it was demonstrated in § 1 that  $\Pi_1 p_k$  (or  $\Pi'_1 v_k$ ) describes in terms of a space frame  $x_k$  both, a vector field  $p_k(v_k)$  and its reflected  $-p_k(-v_k)$ . The operator  $\Pi_1 \Pi'_1 p_k v_k$ , however, measures by  $\Pi_1 \Pi'_1$  only whether both vector fields  $p_k$  and  $v_k$  refer to the same sign  $+p_k$  and  $+v_k$  or  $-p_k$  and  $-v_k$  (we say they have equal reflexion status) or whether they refer to opposite signs,  $+p_k$  and  $-v_k$ , or  $-p_k$  and  $+v_k$ . A distinction between the individual vector fields  $+p_k$  and  $-p_k$ , or between  $+v_k$  and  $-v_k$  does thus not enter our boson wave

equation. The quantity that enters is the distinction as to whether the two have equal or unequal reflexion status. A corresponding result holds for the time components  $p_0, v_0$ . It will be noticed in particular that although  $(i\Pi_2)$  and  $(i\Pi'_2)$  are anti-hermitean, their product is hermitean and thus describes a measurable quantity. While a distinction between the two temporal directions in a single four-vector field is not a measurable quantity, in our theory, the distinction as to whether two four-vector fields have equal or opposite temporal direction (temporal reflexion status) is measurable in terms of the operator  $-\Pi_2\Pi'_2$ . It is of interest to note in this connection that the four function  $\Sigma_\sigma(\Pi)$ , (2.15), (2.16) which simultaneously diagonalise both  $\Pi_1\Pi'_1$  and  $\Pi_2\Pi'_2$  can be expressed in terms of the functions

$$\zeta_+ = \frac{1}{\sqrt{2}} (\xi(\Pi) + \eta(\Pi)), \quad \zeta_- = \frac{1}{\sqrt{2}} (\xi(\Pi) - \eta(\Pi)), \quad (6.1)$$

which have been used in (1.14). For

$$\left. \begin{aligned} \Sigma_1 &= -\frac{i}{\sqrt{2}} (\zeta_+ \zeta'_- + \zeta_- \zeta'_+), & \Sigma_2 &= -\frac{1}{\sqrt{2}} (\zeta_+ \zeta'_+ + \zeta_- \zeta'_-), \\ \Sigma_3 &= \frac{i}{\sqrt{2}} (\zeta_+ \zeta'_+ - \zeta_- \zeta'_-), & \Sigma_4 &= \frac{i}{\sqrt{2}} (\zeta_+ \zeta'_- - \zeta_- \zeta'_+). \end{aligned} \right\} (6.2)$$

As a consequence of the introduction of the operators  $\Pi_l$  and  $\Pi'_l$  the wave equation corresponds now not only to the one classical identity  $p_k v_k - p_0 v_0 + \kappa = 0$  but to four such identities corresponding to replacements of  $p_k v_k$  and  $p_0 v_0$  by  $\pm p_k v_k$  and  $\pm p_0 v_0$  with all four combinations of the  $\pm$  signs. This is easily seen by using a diagonal matrix representation for  $\Pi_1\Pi'_1$  and  $\Pi_2\Pi'_2$ , based on table 1. Classically these combinations of signs would be impossible because of the classical identity  $p_\mu = \kappa v_\mu$  according to which replacement of  $p_k$  by  $-p_k$  entails a replacement of  $v_k$  by  $-v_k$ , leaving  $p_k v_k$  unaltered.

Discussion of the conservation laws derived from wave equation (2.9) has led to the definition of operators for isobaric spin  $T_l$  (2.38) and for electric charge  $Q_3 = R_3(\Pi_3 + \Pi'_3)/2$ , (2.35). It is of considerable interest to discuss the meaning of these operators in terms of the reflexion status of  $(p_k, v_k)$ , i.e. in terms of eigenstates of  $\Pi_1\Pi'_1$  and  $\Pi_2\Pi'_2$  as described above. We shall in particular deal with the electric charge operator  $Q_3$  and notice that in the matrix representation which diagonalises  $\Pi_1\Pi'_1$  and  $\Pi_2\Pi'_2$ , the operator  $(\Pi_3 + \Pi'_3)/2$  is represented by  $q_3$ , (2.44). It acts only on the first two  $\Pi$ -components of the wave function corresponding to the fact that there are only two non zero types of electric charge (positive and negative). Our attention can thus be restricted to these two;



in a formal way they are obtained by operating with  $Q_3^2$  on the wave equation. We then find the two equations,

$$\begin{pmatrix} -1 & \\ & 1 \end{pmatrix} \beta_k \partial_k + \begin{pmatrix} 1 & \\ & -1 \end{pmatrix} \beta_4 \partial_4 + \varkappa, \quad \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = 0 \tag{6.3}$$

because the matrix representations of  $\Pi_1 \Pi'_1$  and  $\Pi_2 \Pi'_2$  are given by  $-\varepsilon_{11}$  and  $-\varepsilon_{22}$  (eqn. 3.6) respectively. Here  $\psi_1$  and  $\psi_2$  stand for  $\Phi_{1\beta}, \Phi_{2\beta}$  in the case of  $\pi$ -meson, or for  $X_{1\beta}, X_{2\beta}$  in the case of  $K$ -meson;  $\varkappa$  represents the respective mass. The  $\pm \beta_k \partial_k$  and  $\pm \beta_4 \partial_4$  show that the charged components correspond for  $\phi_\mu, v_\mu$  either ( $\psi_1$ ) to equal temporal and opposite spacial reflexion status (i.e. both  $\phi_0, v_0$  forward or both backward;  $+\phi_k$  combined with  $-v_k$  or  $-\phi_k$  with  $+v_k$ ) or ( $\psi_2$ ) to opposite temporal and equal spacial reflexion status. The charge operator in terms of the two components  $\psi_1, \psi_2$  is represented by

$$Q_3 \rightarrow R_3 \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \tag{6.4}$$

as obtained from (2.35) and (2.44). It can be brought to principal axes by unitary transformation by

$$G = \frac{1}{\sqrt{2}} \begin{pmatrix} R_2 & iR_1 \\ R_2 & -iR_1 \end{pmatrix}, \quad G Q_3 G^{-1} = \begin{pmatrix} -1 & \\ & 1 \end{pmatrix} \tag{6.5}$$

which combines  $\psi_1$  and  $\psi_2$  into ( $\psi_1$  and  $\psi_2$  are real)

$$\left. \begin{aligned} G \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} &= \begin{pmatrix} \psi \\ \psi^* \end{pmatrix}, & \psi &= R_2 \psi_1 + i R_1 \psi_2 = R_2 (\psi_1 + i R_3 \psi_2) \\ & & \psi^* &= R_2 \psi_1 - i R_1 \psi_2 \end{aligned} \right\} \tag{6.6}$$

where  $\psi, \psi^*$  satisfy the conventional Kemmer equation  $\beta_\mu \partial_\mu + \varkappa, \psi = 0$  and its conjugate complex.

In our theory, therefore, a state with definite electric charge is described by a superposition of a wave function  $\psi_1$  having equal temporal and opposite spacial reflexion status of  $\phi_\mu, v_\mu$  and a wave function  $R_3 \psi_2$  having the opposite temporal and equal spacial reflexion status (combined with an internal space-time reflexion by  $R_3$ ). In fact, electric charge is defined as the operator  $Q_3$  causing an oscillation between these two reflexion states  $\psi_1, \psi_2$ . It is, therefore closely connected with space time reflexions.

At this point it seems worth pointing out that the four-current based on  $\beta_\mu$  vanishes identically in view of the reality conditions, while currents based on  $v_\mu = (i \Pi'_1 \beta_k, -\Pi_2 \beta_4)$  are not conserved. Conserved non vanishing currents depend, of course, on  $v_\mu$  but involve other operators like  $Q_3, T_3$  as well. The electric current density (space component) for instance is from (2.32) and (2.10) obtained as  $\bar{\Psi}(x) Q_3 \Pi_1 \Pi'_1 i \beta_k \Psi(x) =$

$= \bar{\Psi}(x) Q_3 \Pi_1 v_k \Psi(x)$ . We notice (i) that this current contains  $v_k = i \Pi'_1 \beta_k$  only in the form  $\Pi_1 v_k = i \Pi_1 \Pi'_1 \beta_k$  and thus depends on  $\Pi_1 \Pi'_1$  and not on  $\Pi'_1$  alone. Secondly, it refers to a specific quantity  $Q_3$  or  $T_3$  which it carries. Similar remarks hold for the relation of the momentum  $P_\mu = i \int \theta_{4\mu} d^3x$  to the operator  $p_\mu$ .

Definition of the electric charge operator by  $Q_3$  leads to the question of why it is that we choose the third component of  $\mathbf{Q}$  for it. We note, of course, the invariance of the  $\Pi_l, \Pi'_l$  under rotations of the external frame in isospace, but no compelling reason has been given to use the third and not another component. A modification of the wave equation (2.9) can be given which does in fact lead to the desired result, namely replacement of (2.9) by

$$B_\mu \partial_\mu + \Pi_3 \Pi'_3 M, \quad \Psi = 0. \quad (6.7)$$

Clearly only  $Q_3$  and  $T_3$ , but not  $Q_1, Q_2, T_1, T_2$ , lead now to conserved currents. It will be noticed that the energy momentum tensor  $\theta_{\mu\nu}$  defined in (3.14) does not require modification. For  $\partial_\nu \theta_{\mu\nu} = 0$  holds even when (2.9) is replaced by (6.7); on the other hand  $-\theta_{44}$  remains positive, provided the constants  $C$  and  $c$  entering the operator  $M$  are positive. The reality conditions also remain unaltered.

The solutions of the wave equation involved three pairs of Pauli spin operators namely  $\Pi_l, \Pi'_l; \varrho_l, \varrho'_l$  and  $\sigma_l, \sigma'_l$ . Furthermore, in the case of the  $\Pi_l, \Pi'_l$ , an orbital operator  $I$  was introduced. It was then postulated that  $\Psi$  should be antisymmetric under exchange of all pair variables. This led to two types of solutions depending on whether the eigenvalue of  $I^2$  was 0 or 1. In the former case an isobaric spin triplet and a singlet results. The triplet relates to mechanical spin 0 particles ( $\pi$ -mesons) and the singlet to spin particles with zero mass, i. e. it results in the Maxwell equation. The case  $I^2 = 1$  leads to four isobaric spin states both with  $T_3 = \pm 1/2$  as required by  $K$ -mesons. This case yields besides  $K$ -mesons (mechanical spin 0) another two isobaric doublets with mechanical spin 1 and a larger mass than that of  $K$ -mesons ( $\nu$ -particles).

The operator  $I$  is closely connected with the orbital angular momentum in isospace around the 3-axis (the figure axis). Like  $\Pi_3$  and  $\Pi'_3$ ,  $I$  is invariant under rotation in isospace. The definition of an isobaric spin vector  $\mathbf{T}$ , such that  $\mathbf{T} \times \mathbf{T} = i \mathbf{T}$  is satisfied was possible only for the eigenvalues 0 and 1 of  $I^2$ . The physical meaning of this restriction is not clear to me at the moment.

The mass operator  $M$  was introduced such that solutions with different isobaric spin have different rest mass. A very simple form of  $M$  led to nearly the correct mass ratio of  $\pi$ - and  $K$ -mesons. This form of  $M$  has not been derived, however, in a compelling way. Nevertheless, already at this

stage introduction of the  $M$ -operator demonstrates an attitude towards an interpretation of rest mass which is very different from one which regards this quantity as resulting from field self energies. If this attitude is correct then interactions should be formulated in terms of an (improved) mass operator.

*Note added in proof*

1. By replacing in wave equation (2.9) the Kemmer operators  $\beta_\mu$  by Dirac operators, the wave equation for  $\pi$ -mesons based on the symmetric  $\Sigma_e(II)$  functions leads to the wave equation for the electron-neutrino field provided  $M = m q_3^2$  is used. The wave function has then  $3 \times 4 = 12$  components which with an appropriate reality condition provides 6 complex components as required by the 2-component neutrino, 4-component electron theory. Expression (2.35) can still be used for the electric charge operator  $Q_3$ , though  $R_3$  is now a different operator, such that isospin can no longer be defined because (2.40) can not be fulfilled. This operator  $Q_3$  and an appropriate operator for neutrino charge provide automatically the expressions required by hole theory. Electric charge conjugation is still given by (4.11) but parity reflexion can not be separated from neutrino charge conjugation.

2. Careful investigation reveals two types of Lorentz transformations: one which retains complete symmetry in isospace, leaving all  $Q_k$  (and  $T_k$ ) invariant; and a second which leaves only  $Q_3$  invariant and transforms charged and uncharged fields independent of each other.

### References

- 1) H. FRÖHLICH, Proc. Roy. Soc. A 257, 147 (1960); 257, 283 (1960).
- 2) N. KEMMER, Proc. Roy. Soc. A. 173, 91 (1939).
- 3) W. HEISENBERG, Z. Phys. 77, 1 (1932).
- 4) W. PAULI, Rev. Mod. Phys. 13, 203 (1941).