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1) M. Nauenberg and A. Pais, "Wooly Cusps," The Physical Review, Vol. 126, No. 1, April 1, 1962 : pp. 360 - 364.

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Dr. Abraham Pais

Dr. Pais was born in Amsterdam on May 19, 1918. He obtained his Doctor's Degree at the University of Utrecht in 1941. During the years of the occupation, he continued to work under conditions of great difficulty, and the year after the war he was an assistant at the Institute of Theoretical Physics in Copenhagen. In the fall of 1946, Dr. Pais came to the Institute for Advanced Study.

The record of Dr. Pais' work in the last decade is almost a history of the efforts to clarify our understanding of basic atomic theory and of the nature of elementary particles. Pais first proposed the compensation theories of elementary particles, and much of his work has been devoted to exploring the success and limitations of these theories, and indicating the radical character of the revisions which will be needed before they can successfully describe the sub-atomic world. Pais has made important contributions to nuclear theory and to electrodynamics. He is one of the few young theoretical physicists who within the last decade have enriched our understanding of physics.

Statement prepared by J. R. Oppenheimer
Enclosure: Bibliography of papers by Dr. Pais

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(By AP and S.T. Epstein) Note on relativistic properties of self-energies, Revs. Mod. Phys. 21 (1949), 445-446.

(By AP and K.M. Case) On spin-orbit interactions and nucleon-nucleon scattering, Phys. Rev. 80 (1950), p. 203-211.

(By AP and G.E. Uhlenbeck) On Field Theories with Non-Localized Action, Physical Review, Vol. 79, No. 1, 145-165, July 1, 1950.

(By AP and K.M. Case) On High Energy Nucleon-Nucleon Scattering, Physical Review, Vol. 79, No. 1, 185, July 1, 1950.

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JOURNAL OF MATHEMATICAL PHYSICS VOLUME 3, NUMBER 6 NOVEMBER-DECEMBER 1962

On Spinors in n Dimensions*

ABRAHAM PAIS†
Brookhaven National Laboratory, Upton, Long Island, New York
(Received June 29, 1962)

The matrix which enters in the charge conjugation transformation of the usual spinors in 4-space is an invariant matrix and is skew symmetric. It is shown that there exists such an invariant matrix C for any number of dimensions (and independent of the number of time like dimensions). Its symmetry properties depend on the dimension number n *modulo* 8. With the help of the C matrix one can construct, for $n = 1, 2, 7, 8$ mod 8, an n-dimensional invariant bilinear in the components of a *single* n-dimensional spinor. Some examples are given for $n = 2, 3, 7$. A bilinear baryon invariant is formed for a theory with high symmetry. Its existence is closely related to the triality property of 8-space.

I. INTRODUCTION

SPINORS Ψ in n dimensions are multicomponent objects which transform in a specific way [see Eqs. (13) and (18) below] under transformations which leave invariant a quadratic form $E^n = \sum_{i=1}^n \epsilon_i X_i^2$, where $\epsilon_i = \pm 1$. The signature of E^n [given by $(n - m) + m$, where m is the number of minus signs or time like dimensions in E^n] will be immaterial unless otherwise stated. For $n = 2\nu$ or $2\nu + 1$, Ψ has 2^ν spinor components. In general each component may be a function of the X_i. In this note we shall only be concerned with the case that there is no such dependence (constant spinors).

We call Dirac matrices in E^n a set of n matrices Γ_α, $\alpha = 1, \cdots, n$ which satisfy

$$\Gamma_\alpha \Gamma_\beta + \Gamma_\beta \Gamma_\alpha = 2\,\delta_{\alpha\beta} \cdot I, \qquad \alpha, \beta = 1, \cdots, n, \tag{1}$$

where I is the unit matrix. For $n = 2\nu$ and $2\nu + 1$ these relations can be satisfied by Γ's which are $2^\nu \times 2^\nu$ matrices.

It is well known[1] that the Γ_α can be expressed as direct products (also called Kronecker products or tensor products) of the Pauli spin matrices

$$\sigma_x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \sigma_y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, \quad \sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \tag{2}$$

This is quite familiar in the case $n = 4$ where, for example, we can take

$$\Gamma_1 = \sigma_x^{(1)} \times \sigma_x^{(1)}, \quad \Gamma_2 = \sigma_x^{(1)} \times \sigma_y^{(2)},$$
$$\Gamma_3 = \sigma_x^{(1)} \times \sigma_z^{(2)}, \quad \Gamma_4 = \sigma_y^{(1)}. \tag{3}$$

The superscripts (1), (2) refer to two distinct sets of Pauli matrices and the notation $\times$ denotes direct product. For example to get Γ_2, first write down a matrix σ_x, but consider its elements as 2×2 null and unit matrices, respectively. Next multiply each of these four matrices by the 2×2 matrix $\sigma_y^{(2)}$, so that

$$\Gamma_2 = \begin{bmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \end{bmatrix}.$$

The direct multiplication process can be repeated. For example to obtain $\Gamma_2 \times \sigma_z^{(3)}$, consider the elements 0 and $\pm i$ of Γ_2 as 2×2 null matrices and $\pm i$ times 2×2 unit matrices, respectively, and multiply each of these matrices with σ_z. For $n = 2\nu$ or $2\nu + 1$ we shall need direct products of ν matrices of the kinds $\sigma_x^{(i)}$, $\sigma_y^{(i)}$, $\sigma_z^{(i)}$, $1^{(i)}$, $i = 1, \cdots, \nu$, where $1^{(i)}$ is the ith 2×2 unit matrix.

This construction procedure for Dirac matrices makes it considerably simpler to derive and understand some results due to Cartan.[2] In his book on spinors a more geometrical reasoning is used which, I believe, makes the derivations for general n unduly cumbersome. There are several interesting theorems on bilinear spinor covariants which depend in a nontrivial way on n *modulo* 8. These can all be obtained by asking, in the language of the physicists, the following question. What is the n-dimensional generalization of the familiar charge conjugation matrix C?

Briefly, C is a unitary, skew symmetric matrix and is invariant under the full Lorentz group.[3] In any given representation, C considered as a unitary transformation sends any of the n Dirac

* Work supported, in part, by the U. S. Atomic Energy Commission.

† Permanent address: The Institute for Advanced Study, Princeton, New Jersey.

[1] R. Brauer and H. Weyl, Am. J. Math. 57, 447 (1935).

[2] E. Cartan, *Leçons sur la theorie des spineurs* (Hermann and Cie, Paris, 1938), 2 vols. Actualités Scientifiques, Nos. 643, 701.

[3] For a discussion of the properties of C, see e. g., A. Pais and R. Jost, Phys. Rev. 87, 871 (1952).

matrices into its transposed. In the next section we construct a unitary and invariant matrix C for any dimension. The interesting thing is the way the symmetry of C depends on the dimension number, see Eqs. (9) and (25) below. In Sec. III we give some illustrations for two-, three-, and seven-dimensional rotation groups.

II. THE C MATRIX

(A) Even Dimensions, $E^{2\nu}$

Lemma. There exists a representation in which all Γ_α are Hermitian, half of them are symmetric (real), the other half antisymmetric (imaginary). One way of achieving this is as follows:

$$\begin{aligned}\Gamma_1 &= \Lambda_\nu,\\ \left.\begin{aligned}\Gamma_{2m} &= \Lambda_{\nu-m}\times\sigma_y^{(\nu-m+1)}\times 1^{(\nu-m+2)}\times\cdots\times 1^{(\nu)},\\ \Gamma_{2m+1} &= \Lambda_{\nu-m}\times\sigma_z^{(\nu-m+1)}\times 1^{(\nu-m+2)}\times\cdots\times 1^{(\nu)},\end{aligned}\right\} & \quad m = 1,\cdots,\nu-1 \\ \Gamma_{2\nu} &= \sigma_y^{(1)}\times 1^{(2)}\cdots\times 1^{(\nu)},\end{aligned}\tag{4}$$

where

$$\Lambda_m = \sigma_z^{(1)}\times\sigma_z^{(2)}\times\cdots\times\sigma_z^{(m)}. \tag{5}$$

For $n = 2$ this reduces to Eq. (3). It is easy to see that Eq. (1) is satisfied. As the σ's are Hermitian, so are the Γ's. Furthermore

$$\Gamma^t_{2\alpha-1} = \Gamma_{2\alpha-1},\qquad \Gamma^t_{2\alpha} = -\Gamma_{2\alpha}, \tag{6}$$

where t denotes transposition. Equation (6) is true because the transposed of a direct product equals the direct product of the transposed factors.

We now define the "charge conjugation matrix" C by

$$C = \prod_{\alpha=1}^{\nu}\Gamma_{2\alpha-1}. \tag{7}$$

C has three main properties. First,

$$C^\dagger C = 1. \tag{8}$$

Secondly, from Eqs. (1) and (6)

$$\begin{aligned}C^t = (-1)^{(\nu/2)(\nu-1)}C &= C,\quad \nu = 0,\ 1 \bmod 4,\\ &= -C,\quad \nu = 2,\ 3 \bmod 4.\end{aligned}\tag{9}$$

Finally, it follows from Eqs. (1) and (7) that $C\Gamma_\alpha = (-1)^{\nu+\epsilon}\Gamma_\alpha C$ where $\epsilon = 0(1)$ for $\alpha =$ even (odd). Hence using Eq. (6)

$$C\Gamma_\alpha = (-1)^{\nu+1}\Gamma^t_\alpha C. \tag{10}$$

Thus for $\nu = 2$, Eqs. (8), (9), and (10) show that C has the familiar properties.[3]

Next consider the behavior of C under the following kinds of transformations.

(a) *Change of Γ Representation*

$$\Gamma'_\mu = S^{-1}\Gamma_\mu S. \tag{11}$$

The corresponding C' is defined so as to preserve Eq. (10) so that

$$C' = S^t C S. \tag{12}$$

It follows that C' again satisfies Eqs. (8) and (9).

(b) *Invariance of C under Rotations*

An infinitesimal rotation on the 2^ν-component spinor Ψ is given by

$$\Psi' = S\Psi,\quad S = 1 + \tfrac{1}{4}\epsilon_{\rho\sigma}\Gamma_\rho\Gamma_\sigma,\quad \epsilon_{\rho\sigma} = -\epsilon_{\sigma\rho}. \tag{13}$$

Under this *specific* S-transformation $C' = C$, from Eqs. (10) and (12). Note that the reality properties of $\epsilon_{\rho\sigma}$ do not enter the discussion here, so that these results are independent of the signature of the metric.

(c) *Invariance of C under Reflections*

At this point it is helpful to introduce the generalization of the customary γ_5 matrix, namely,

$$\Gamma_{2\nu+1} = (-i)^\nu\prod_{\alpha=1}^{2\nu}\Gamma_\alpha. \tag{14}$$

In the special representation of Eqs. (4) and (5) we have

$$\Gamma_{2\nu+1} = \sigma_z^{(1)} = \begin{bmatrix} I_{\nu-1} & 0\\ 0 & -I_{\nu-1}\end{bmatrix}, \tag{15}$$

where $I_{\nu-1}$ is the $2^{\nu-1}$-dimensional unit matrix. Thus

$$\Gamma^t_{2\nu+1} = \Gamma_{2\nu+1}, \tag{16}$$

while from Eqs. (6), (10), and (14) we obtain

$$C\Gamma_{2\nu+1} = (-1)^\nu\Gamma^t_{2\nu+1}C. \tag{17}$$

Consider the coordinate reflection in $E^{2\nu}: X'_\alpha = -X_\alpha$, $X'_\beta = X_\beta$, $\beta \neq \alpha$, $\alpha = 1$ or $2 \cdots$ or 2ν. There is an ambiguity in the definition of the behavior of Ψ

under reflections. We may put

$$\Psi' = S_\alpha \Psi, \qquad S_\alpha = i\Gamma_\alpha \Gamma_{2\nu+1}. \tag{18}$$

With this choice, C is also invariant under reflections, as follows from Eqs. (12) and (17). Thus Eqs. (8), (9), and (10) are invariant and independent of the choice of representation.

Bilinear covariants. We have at once that the quantity T, defined by

$$T = \Psi^t C \Psi, \tag{19}$$

is a scalar with respect to the full n-dimensional rotation group (i.e., including reflections). For $T' = \Psi^t S^t C S \Psi = T$. However, it is evident that $T \equiv 0$ if[4] $C^t = -C$. Therefore

$$T \not\equiv 0 \quad \text{if} \quad \nu = 0, 1 \bmod 4, \tag{20}$$

that is, in 2, 8, $\cdots$ dimensions. The extension to tensors of higher rank is trivial. Thus $\Psi^t C(\Sigma \pm \Gamma_{\mu_1} \cdots \Gamma_{\mu_p})\Psi$ is a tensor[5] of rank p which is $\not\equiv 0$ for $\nu(\nu-1) + 2p(\nu+1) + p(p-1) = 0 \bmod 4$. In particular, for $p = 2\nu$ we get a nonvanishing "pseudoscalar" for $\nu(\nu+1) = 0 \bmod 4$.

Bilinear covariants excluding reflections. It follows from Eq. (15) that in the special representation Eq. (14) the quantities

$$\Psi_\pm = [(1 \pm \Gamma_{2\nu+1})/2]\Psi \tag{21}$$

have, in general, $2^{\nu-1}$ nonvanishing components. These are the so-called semispinors of first and second kind. Define

$$T_\pm = \Psi_\pm^t C \Psi_\pm. \tag{22}$$

These are scalars with respect to the restricted group where reflections are excluded. From Eqs. (16) and (17), $T_+ \not\equiv 0$ for $\nu = 0 \bmod 4$. Likewise $T'_\pm = \Psi_\pm^t C \Psi_\mp \not\equiv 0$ for $\nu = 1 \bmod 4$. The construction of higher rank tensors in terms of semi-spinors is obvious.

(B) Odd Dimensions, $E^{2\nu+1}$

According to Eq. (15), $\Gamma_{2\nu+1}^2 = 1$, and furthermore $\Gamma_{2\nu+1}$ anticommutes with all Γ_α, $\alpha = 1, \cdots, 2\nu$. For $2\nu + 1$ dimensions a representation of the Dirac matrices is therefore given by Eqs. (4) and (15). Define

$$C = \prod_{\alpha=1}^{\nu+1} \Gamma_{2\alpha-1}. \tag{23}$$

[4] The components of Ψ are supposed to commute.

[5] $\Sigma\, +$ denotes the alternating sum over permutations of $(1, \cdots, p)$.

One has

$$C^\dagger C = 1, \tag{24}$$

$$C^t = (-1)^{(\nu/2)(\nu+1)} C, \tag{25}$$

$$C\Gamma_\alpha = (-1)^\nu \Gamma_\alpha^t C. \tag{26}$$

The transformation Eq. (12) holds true here too. So does the invariance of C under rotations. We need not consider reflections. We have

$$T = \Psi^t C \Psi \not\equiv 0, \qquad \nu = 0, 3 \bmod 4, \tag{27}$$

and of course T is a scalar. Tensors of higher rank are discussed as under (A).

Expressions like Eqs. (19), (22), and (27) can of course be generalized to $\Phi^t C \Psi$, where Φ, Ψ are two distinct spinors. For $\Phi \neq \Psi$ the corresponding scalars and other covariants clearly are in general nonzero for any dimension.

III. APPLICATIONS

(1) For orientation, consider the familiar instance $n = 3$. We are in case (B), $\nu = 1$ and according to the recipe of Eq. (4), $\Gamma_1 = \sigma_x$, $\Gamma_2 = \sigma_y$, $\Gamma_3 = \sigma_z$, so from Eq. (23), $C = -i\sigma_y$. Consider two spinors $\Phi^t = [\alpha(1), \beta(1)]$ and $\Psi^t = [\alpha(2), \beta(2)]$. α and β denote the eigenstates for spin up and down, respectively. The "arguments" 1 and 2 simply denote that we deal with two distinct spinors. The scalar $\Phi^t C \Psi = -\alpha(1)\beta(2) + \alpha(2)\beta(1)$. This is of course the two-particle singlet state. Now put "$1 = 2$," that is, take the scalar $\Phi^t C \Phi$. This vanishes identically.

Thus Eqs. (20) and (27) say that only for dimensions $n = 1, 2, 7, 8 \bmod 8$ is it possible to form a nonvanishing singlet state bilinear in one single spinor.

(2) As the simplest example for a nonvanishing invariant take $n = 2$. We have case (A), $\nu = 1$. Thus $\Gamma_1 = \sigma_x$, $\Gamma_2 = \sigma_y$, $C = \sigma_z$. Therefore $\Phi^t C \Psi = \alpha(1)\beta(2) + \alpha(2)\beta(1)$. This quantity is indeed a scalar for rotations in the xy plane, as it is the z component of the spin 1-vector in 3-space. And $\Phi^t C \Phi$ indeed does not vanish.

(3) A less trivial example of a nonzero scalar is provided by the seven-dimensional charge space formalism of baryon meson interactions.[6] Here the coupling $\bar\Psi \Gamma_\mu \Psi \Phi_\mu$ is considered with

$$\Psi^t = \left(p, n, \Xi^0, \Xi^-, \Sigma^+, \frac{\Lambda - \Sigma^0}{\sqrt{2}}, \frac{\Lambda + \Sigma^0}{\sqrt{2}}, \Sigma^-\right) \tag{28}$$

[6] First given by J. Tiomno, Nuovo cimento **6**, 69 (1957).

$$\Phi_\mu = \left(\frac{K^- + K^+}{\sqrt{2}}, \frac{K^- - K^+}{i\sqrt{2}}, \frac{\bar{K}^0 + K^0}{\sqrt{2}}, \frac{\bar{K}^0 - K^0}{i\sqrt{2}}, \frac{\pi^- + \pi^+}{\sqrt{2}}, \frac{\pi^- - \pi^+}{i\sqrt{2}}, \pi_0\right), \quad (29)$$

$$\Gamma_\mu = \sigma_x^{(1)} \times \sigma_y^{(2)} \times 1^{(3)}, \quad \sigma_z^{(1)} \times \sigma_y^{(2)} \times 1^{(3)}, \quad \sigma_z^{(1)} \times \sigma_z^{(2)} \times 1^{(3)}, \quad \sigma_y^{(1)} \times 1^{(2)} \times 1^{(3)}, \quad \sigma_z^{(1)} \times 1^{(2)} \times \sigma_x^{(3)}, \quad \sigma_z^{(1)} \times 1^{(2)} \times \sigma_y^{(3)}, \quad \sigma_z^{(1)} \times 1^{(2)} \times \sigma_z^{(3)}. \quad (30)$$

Ψ is an 8-component spinor with respect to charge space. Each of its components is a 4-spinor with respect to Lorentz space. We shall denote by Ψ_A, $A = 1, 2, 3$ or 4 the four quantities obtained by taking the same Ath Lorentz space component of each charge space component. Each Ψ_A transforms as a spinor under the seven-dimensional rotation group.

The Γ representation of Eq. (30) is not like Eqs. (4) and (15) but it does satisfy Eqs. (6) and (16). We can therefore apply the formalism of case (B) with $\nu = 3$. Thus $C = -1^{(1)} \times \sigma_y^{(2)} \times \sigma_y^{(3)}$. Define T_{AB} by

$$T_{AB} = \Psi_A^t C \Psi_B = \Lambda_A \Lambda_B - (\Sigma_A^+ \Sigma_B^- + \Sigma_A^0 \Sigma_B^0 + \Sigma_A^- \Sigma_B^+) - (p_A \Xi_B^- - n_A \Xi_B^0) - (\Xi_A^- p_B - \Xi_A^0 n_B). \quad (31)$$

For all $A, B = 1, \cdots, 4$, T_{AB} is a nonvanishing scalar with respect to the 7-group. The same is true for $\bar{T}_{AB} \equiv \bar{\Psi}_A^t C \bar{\Psi}_B$.

T_{AB} is of course also a scalar with respect to any subgroup of the 7-group, but then it breaks up in separate parts invariant with respect to that subgroup. An obvious example is the isotopic spin with respect to which T_{AB} clearly consists of four additive scalar parts. A less trivial case is the exceptional group $G2$ with respect to which $\Lambda_A \Lambda_B$ and $T_{AB} - \Lambda_A \Lambda_B$ are separate scalars. For example the finite angle rotations of $G2$ explicitly given by Behrends and Sirlin[7] are seen to leave $\Lambda_A \Lambda_B$ and $T_{AB} - \Lambda_A \Lambda_B$ separately invariant.

There begins to emerge a certain three-way equivalence for the baryon, the antibaryon (each in a given spin state) and the meson. For each there exists a bilinear invariant, namely, T_{AA}, $\bar{T}_{AA}$ and $\phi_\mu^2 = \bar{K}K + K\bar{K} + \pi^2$, respectively. Let us introduce an additional meson state σ with zero spin and hypercharge which forms an octet with π and K. Now all three quantities are 8-component. The structures now before us are just the ones which play a role in the principle of triality,[8] unique for dimension eight. Briefly stated, triality is a certain substitutional invariance (involving the alternating group on three things) between vectors, semispinors of the first kind and semispinors of the second kind in an 8-space which leaves invariant a trilinear form. In our case this form is $\bar{\Psi}\Gamma_\mu\Psi\phi_\mu + \bar{\Psi}\Psi\sigma$. Note that such a substitutional invariance is conceivable only in an 8-space, because only for that dimension do vectors and semispinors of either kind all have the same number of components. Triality invariance is very closely connected with the octonion formulation of interactions given elsewhere.[9] If applicable, the principle of triality would state that the baryon, the antibaryon and the meson have identical properties of higher symmetry and that the interaction should be such that these three objects are interchangeable (with respect to their intrinsic symmetries) as is the case for their trilinear invariant. In all this we have not insisted on the spatial transformation properties such as the spin zero character of the meson.

In all the foregoing, the signature of the metric played no role. This only enters when we have to consider simultaneously a spinor and its adjoint. Let the directions $h, k, \cdots$ be timelike. Then the adjoint of Ψ is $\bar{\Psi} = \Psi^\dagger \Gamma_h \Gamma_k \cdots$.

It is well known that familiar charge conjugation can only be formulated consistently in a quantized theory. Likewise the desired change of sign of the 4-current is also closely related to the 3 + 1 signature of the metric.

Consider as a last example a 7-space with signature 6 + 1. Let "4" be the timelike direction. Form the current $\bar{\Psi}\Gamma_\mu\Psi$, $\bar{\Psi} = \Psi^\dagger\Gamma_4$. Perform now a charge conjugation $\Psi' = C^{-1}\bar{\Psi}^t$. Taking the adjoint of this gives $\bar{\Psi}' = -\Psi^t C$. [We are in case (B) with $\nu = 3$.] Note how this minus sign is closely connected with the oddness of the number of timelike directions. Now let $\Psi^\dagger$ and Ψ anticommute. Then $(\bar{\Psi}\Gamma_\mu\Psi)' = -(\bar{\Psi}\Gamma_\mu\Psi)$.

This property is isomorphic to G conjugation. This is seen as follows. A representation of the Γ_μ is provided by $\Gamma_\mu = \gamma_\mu$, $\mu = 1\text{-}4$, $\Gamma_{5,6,7} = \gamma_5\tau_{1,2,3}$. Here the γ_μ are the usual four Dirac matrices and τ_i is the isotopic spin vector. Take γ_1 and γ_3 real, γ_2 and γ_4 imaginary, and apply the general formulas. This gives $C_7 = \gamma_1\gamma_3 \cdot -i\tau_2 = C_4 \cdot -i\tau_2$. C_7 is the over-all charge conjugation matrix, C_4 is the corre-

[7] R. Behrends and A. Sirlin, Phys. Rev. **121**, 324 (1961), Table I.

[8] Reference 2, Vol. 2, p. 53.

[9] A. Pais, Phys. Rev. Letters **7**, 291 (1961).

sponding matrix for Lorentz space. Thus C_7 is the G-conjugation operator. The 1–4 components of $\bar{\Psi}\Gamma_\mu\Psi$ are the baryon current and the 5–7 components are the π-meson source. Together, these form a *vector* in a 7-space.

The enlarged current structure is just due to the fact that π is pseudoscalar.[10] If we use the Γ's of Eq. (30) and denote them now as $\Gamma_\alpha^{(7)}$ we get again such a structure, namely, $\Gamma_a = (\gamma_\mu, \gamma_5\Gamma_\alpha^{(7)})$. The Γ_a again satisfy Eq. (1) and $\bar{\Psi}\Gamma_a\Psi$ is again a *vector*, just because π and K are pseudoscalar. This current consists of baryon current, π and K sources. There exists a corresponding conjugation, enlarging G conjugation (with $K \rightarrow -K$) just as G conjugation enlarges charge conjugation. It would be interesting if, along with the enlarged conjugation one could also enlarge the gauge principle.

[10] However, a scalar π with scalar coupling would also be odd under G.

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Correlations Between Cusps in Differential Cross Sections and in Polarizations

M. Nauenberg and A. Pais

Institute for Advanced Study, Princeton, New Jersey

Abstract

Experiments have shown that partial waves with $\ell > 1$ appear in $\pi^- + p \rightarrow \Lambda + K^0$ at the ΣK-thresholds. This necessitates a reconsideration of the criteria sufficient to determine the $\Sigma\Lambda$-parity $P(\Sigma\Lambda)$ by the method of cusps. In this paper we start from the usual assumption that contributions which show a cusp in either the differential cross section or the polarization may be ignored beyond some optimal power in $\cos\theta$. On this sole basis previously stated criteria are rendered inadequate due to the occurrence of Minami and other ambiguities. It is shown that under suitable circumstances there exist unambiguous correlations between certain properties of cross section cusps and of polarization cusps. These correlations could possibly be of use to determine $P(\Sigma\Lambda)$ and give information as to which states contribute significantly to the ΛK production at ~ 900 Mev. The finite separation between $\Sigma^0 K^0$- and $\Sigma^- K^+$-thresholds is taken into account. The results are summarized in a table of cusp properties.

Pais

Electromagnetic Effects on Decays of G-Eigenstates*

G. Feinberg+

Department of Physics, Columbia University, New York, New York

and

A. Pais

Institute for Advanced Study, Princeton, New Jersey

*Work supported in part by the U. S. Atomic Energy Commission

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Pais

On Spinors in n Dimensions*

Abraham Pais+
Brookhaven National Laboratory, Upton, New York

Abstract

The matrix which enters in the charge conjugation transformation of the usual spinors in 4-space is an invariant matrix and is skew symmetric. It is shown that there exists such an invariant matrix C for any number of dimensions (and independent of the number of time like dimensions). Its symmetry properties depend on the dimension number n modulo 8. With the help of the C matrix one can construct, for n = 1, 2, 7, 8 mod 8 an n-dimensional invariant bilinear in the components of a single n-dimensional spinor. Some examples are given for n = 2, 3, 7. A bilinear baryon invariant is formed for a theory with high symmetry. Its existence is closely related to the triality property of 8-space.

*Work supported, in part, by the U. S. Atomic Energy Commission

+Permanent address, The Institute for Advanced Study, Princeton, New Jersey

Submitted to Journal of Mathematical Physics

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24 July 1962

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650	34.10	49.10	72.60	108.60	125.90	151.20	183.40	217.50	235.20
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750	36.10	53.10	78.75	118.75	138.00	165.40	201.20	239.75	259.40
800	37.10	55.10	81.75	123.75	144.00	172.50	210.75	250.90	271.50
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21 June 1962

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Toward the cost of publication at $ 45.00 per page

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Article: Properties and Effects of..Decays

Journal: PHYSICAL REVIEW LETTERS

Issue: APRIL 15, 1962

No. of Pages: 341-343

2.40 pages @ $45.00 per page:	$108.00
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AUTHOR (S). G. Feinberg and A. Pais

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A. Pais
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AUTHOR (S). M. Nauenberg and A. Pais

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300	26.50	34.50	800	37.10	55.10
350	27.75	36.60	850	38.00	57.00
400	29.00	38.75	900	38.90	58.75
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Journal:	REVIEWS OF MODERN PHYSICS	
Issue:	July, 1961	
No. of Pages:	5-8	
No. of Reprints:	100	$28.75
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American Institute of Physics REVIEWS OF MODERN PHYSICS

July 1961

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PUBLISHED ARTICLE

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Journal: THE PHYSICAL REVIEW

Issue: April 1, 1961

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	Journal: The Physical Review 122			
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250	25.50	32.25	46.50	65.60	74.25	90.40	105.75	122.90	131.20
300	26.50	34.50	49.90	71.20	80.90	98.25	115.75	135.20	145.00
350	27.75	36.60	53.25	76.75	87.70	106.20	125.90	147.40	158.50
400	29.00	38.75	56.60	82.25	94.25	114.00	135.90	159.70	171.90
450	30.00	41.00	60.00	87.90	101.00	121.90	146.00	171.90	185.40
500	31.10	43.10	63.50	93.40	107.70	129.75	156.00	184.20	198.75
550	32.10	45.10	66.50	98.50	113.75	136.90	165.20	195.25	210.90
600	33.10	47.10	69.50	103.50	119.75	144.00	174.25	206.40	223.00
650	34.10	49.10	72.60	108.60	125.90	151.20	183.40	217.50	235.20
700	35.10	51.10	75.60	113.60	131.90	158.25	192.50	228.70	247.25
750	36.10	53.10	78.75	118.75	138.00	165.40	201.20	239.75	259.40
800	37.10	55.10	81.75	123.75	144.00	172.50	210.75	250.90	271.50
850	38.00	57.00	84.50	128.40	149.50	178.90	219.00	260.90	282.50
900	38.90	58.75	87.25	132.90	154.90	185.25	227.20	270.90	293.20
950	39.80	60.60	90.00	137.50	160.40	191.70	235.40	280.90	304.00
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2/20/61

Verna,

Dr. Pais would 150 copies ordered for the Institute and 50 copies for himself. We already have a great number of requests for this reprint.

Jane

Pais ✓

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March 8, 1960

Publishers of Physics Journals

Institute for Advanced Study
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PHYSICAL REVIEW.

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January 12, 1960

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issue of The Physical Review 116

Article:	On the Quantum Theory of the Third Virial Coefficient	
Author:	A. Pais and G. E. Uhlenbeck	
Appearing on page Nos.:	250-269	
No. of pages:	20 pages @ $30.00 per page	$600.00
Charge for advance publication of abstract of above article in Physical Review Letters		8.00
Amount Due		$608.00

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FORM A159

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New York 17, New York

The Physical Review ....

Scheduled Issue .... October 15, 1959

TITLE OF ARTICLE ...... Quantum Theory of the Third Virial Coefficient

AUTHOR .... A. Pais and G. E. Uhlenbeck

PUBLICATION CHARGE CERTIFICATION

(In the absence of the following authorization, reprints will be furnished at list prices. See back of this form.)

I shall authorize the payment of $30.00 per page in partial support of the publication of this article, as well as an $8.00 payment for the advance publication of its Abstract in Physical Review Letters. I understand that this entitles us to 100 free reprints without covers or a credit toward a larger purchase in accordance with the following schedule:

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4 November 1959 .... A Pais
Date — Signature of Author

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200	24.50	30.00	43.10	60.00	67.50	82.50	95.70	110.70	118.20
250	25.50	32.25	46.50	65.60	74.25	90.40	105.75	122.90	131.20
300	26.50	34.50	49.90	71.20	80.90	98.25	115.75	135.20	145.00
350	27.75	36.60	53.25	76.75	87.70	106.20	125.90	147.40	158.50
400	29.00	38.75	56.60	82.25	94.25	114.00	135.90	159.70	171.90
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500	31.10	43.10	63.50	93.40	107.70	129.75	156.00	184.20	198.75
550	32.10	45.10	66.50	98.50	113.75	136.90	165.20	195.25	210.90
600	33.10	47.10	69.50	103.50	119.75	144.00	174.25	206.40	223.00
650	34.10	49.10	72.60	108.60	125.90	151.20	183.40	217.50	235.20
700	35.10	51.10	75.60	113.60	131.90	158.25	192.50	228.70	247.25
750	36.10	53.10	78.75	118.75	138.00	165.40	201.20	239.75	259.40
800	37.10	55.10	81.75	123.75	144.00	172.50	210.75	250.90	271.50
850	38.00	57.00	84.50	128.40	149.50	178.90	219.00	260.90	282.50
900	38.90	58.75	87.25	132.90	154.90	185.25	227.20	270.90	293.20
950	39.80	60.60	90.00	137.50	160.40	191.70	235.40	280.90	304.00
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450	42.00	27.40
500	45.75	29.50
550	49.40	31.50
600	53.00	33.50
650	56.70	35.50
700	60.25	37.50
750	63.90	39.50
800	67.50	41.50
850	71.20	43.50
900	74.75	45.50
950	78.40	47.50
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Pais

1 July 1959

Memorandum to Mr. Morgan:

Will you please bill Department of Physics, Columbia University, New York 27, New York, attention Mrs. Bolton, for $59.25, to be credited to the Publications Fund. This is their share of charges for support of publication and reprints of the article by A. Pais and R. Serber, "General Transformation of the Symmetrical Pseudo-scalar Theory", Phys. Rev. February 1, 1959. We have paid two bills to the American Institute of Physics, as follows:

Toward the cost of publication	$100.00	
Charge for abstract in Phys.Rev.Letters	7.00	
		$107.00
300 reprints (of which 150 shipped to Dr. Serber at Columbia)		$ 11.50
		$118.50
1/2 to be paid by Columbia		$ 59.25

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Publishers of Physics Journals

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R.
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issue: PHYSICAL REVIEW.

300 reprints, 3-4 pages (first 100 given free
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150 reprints were shipped to Director's Office and
150 reprints were shipped to Dr. R.Serber at Columbia University

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Publishers of Physics Journals

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Toward the cost of publication at \$25.00 per page in the February 1, 1959 issue of The Physical Review

Article:	A General Transformation of the Symmetrical Pseudoscalar Theory	
Author:	A. Pais and R. Serber	
Appearing on page Nos.:	955-958	
No. of pages:	4 pages @ \$ 25.00 per page,	\$ 100.00
Charge for advance publication of abstract of above article in Physical Review Letters		7.00
Amount Due		\$ 107.00

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AUTHOR A. Pais and R. Serber

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250	20.40	25.80	37.20	52.50	59.40	72.30	84.60	98.30	105.30
300	21.30	27.50	39.90	56.90	64.70	78.60	92.60	108.10	116.00
350	22.20	29.30	42.60	61.40	70.10	84.90	100.70	117.90	126.80
400	23.10	31.00	45.30	65.80	75.40	91.20	108.70	127.70	137.50
450	24.00	32.80	48.00	70.30	80.80	97.50	116.80	137.50	148.30
500	24.90	34.50	50.70	74.70	86.10	103.80	124.80	147.30	159.00
550	25.70	36.10	53.20	78.80	91.00	109.50	132.10	156.20	168.70
600	26.50	37.70	55.60	82.80	95.80	115.20	139.40	165.10	178.40
650	27.30	39.30	58.10	86.90	100.70	120.90	146.70	174.00	188.10
700	28.10	40.90	60.50	90.90	105.50	126.60	154.00	182.90	197.80
750	28.90	42.50	63.00	95.00	110.40	132.30	161.30	191.80	207.50
800	29.70	44.10	65.40	99.00	115.20	138.00	168.60	200.70	217.20
850	30.40	45.60	67.60	102.70	119.60	143.10	175.20	208.70	225.90
900	31.10	47.00	69.80	106.30	123.90	148.20	181.70	216.70	234.50
950	31.80	48.50	72.00	110.00	128.30	153.30	188.30	224.70	243.20
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500	36.60	23.60	
550	39.50	25.20	
600	42.40	26.80	
650	45.30	28.40	
700	48.20	30.00	
750	51.10	31.60	
800	54.00	33.20	
850	56.90	34.80	
900	59.80	36.40	
950	62.70	38.00	
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BULLETIN OF AMERICAN PHYSICAL SOCIETY
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February 18, 1959

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~~Vol II~~
Vol 1 # 11 p 418

Article by A. Pais in the December 1, 1958 issue:

PHYSICAL REVIEW LETTERS

Publication charge 1.80 pages @ $ 25.00 per page,	$ 45.00
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FORM G557

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TITLE OF ARTICLE.... Parity and Other Symmetries in Strong Interactions
AUTHOR... A. Pais

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200	19.50	24.00	34.50	48.00	54.00	66.00	76.50	88.50	94.50
250	20.40	25.80	37.20	52.50	59.40	72.30	84.60	98.30	105.30
300	21.30	27.50	39.90	56.90	64.70	78.60	92.60	108.10	116.00
350	22.20	29.30	42.60	61.40	70.10	84.90	100.70	117.90	126.80
400	23.10	31.00	45.30	65.80	75.40	91.20	108.70	127.70	137.50
450	24.00	32.80	48.00	70.30	80.80	97.50	116.80	137.50	148.30
500	24.90	34.50	50.70	74.70	86.10	103.80	124.80	147.30	159.00
550	25.70	36.10	53.20	78.80	91.00	109.50	132.10	156.20	168.70
600	26.50	37.70	55.60	82.80	95.80	115.20	139.40	165.10	178.40
650	27.30	39.30	58.10	86.90	100.70	120.90	146.70	174.00	188.10
700	28.10	40.90	60.50	90.90	105.50	126.60	154.00	182.90	197.80
750	28.90	42.50	63.00	95.00	110.40	132.30	161.30	191.80	207.50
800	29.70	44.10	65.40	99.00	115.20	138.00	168.60	200.70	217.20
850	30.40	45.60	67.60	102.70	119.60	143.10	175.20	208.70	225.90
900	31.10	47.00	69.80	106.30	123.90	148.20	181.70	216.70	234.50
950	31.80	48.50	72.00	110.00	128.30	153.30	188.30	224.70	243.20
1000	32.50	49.90	74.20	113.60	132.60	158.40	194.80	232.70	251.80
Additional 50's over 1000	.70	1.30	2.00	3.30	3.90	4.50	5.80	7.10	7.60

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350	27.60	18.50
400	30.60	20.20
450	33.60	21.90
500	36.60	23.60
550	39.50	25.20
600	42.40	26.80
650	45.30	28.40
700	48.20	30.00
750	51.10	31.60
800	54.00	33.20
850	56.90	34.80
900	59.80	36.40
950	62.70	38.00
1000	65.60	39.60
Additional 50's	2.80	1.50

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THE JOURNAL OF CHEMICAL PHYSICS
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January 26, 1959

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Article by A. Pais in the October 15, 1958 issue:

THE PHYSICAL REVIEW

150 reprints, 17-20 pages, (first 100 given free in
consideration of the publication charge), $ 14.10

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2/5

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December 4, 1958

335 EAST 45 STREET, NEW YORK 17, N. Y.
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Publishers of Physics Journals

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(2) V 112 2-91-680

Toward the cost of publication at $25.00 per page in the October 15, 1958 issue of The Physical Review

Article: Relative Parity of Charged and Neutral K- Particles

Author: A. Pais

Appearing on page Nos.: 624-641

No. of pages: 18 pages @ $ 25.00 per page, $ 450.00

Charge for advance publication of abstract of above article in Physical Review Letters 7.00

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AUTHOR A. Pais

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Pages: 574-578

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Article: Note on Relations between Baryon-Meson Coupling Constants

Author: A. Pais

Published in: THE PHYSICAL REVIEW

Issue: June 15, 1958

Pages: 1480

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550	39.50	25.20
600	42.40	26.80
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Issue: March 1, 1958

Pages: 1759-1762

3.40 pages @ $ 25.00 per page, $ 85.00

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FORM B553

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Journal: Physical Review

Scheduled Issue: March 1, 1958

TITLE OF ARTICLE: Polarization Effects in Σ^--capture

AUTHOR: A. Pais and S. B. Trieman

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450	24.00	32.80	48.00	70.30	80.80	97.50	116.80	137.50	148.30
500	24.90	34.50	50.70	74.70	86.10	103.80	124.80	147.30	159.00
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700	28.10	40.90	60.50	90.90	105.50	126.60	154.00	182.90	197.80
750	28.90	42.50	63.00	95.00	110.40	132.30	161.30	191.80	207.50
800	29.70	44.10	65.40	99.00	115.20	138.00	168.60	200.70	217.20
850	30.40	45.60	67.60	102.70	119.60	143.10	175.20	208.70	225.90
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MESSAGE

TO: Verna Hobson

FROM: J. L. Kane DATE: 2/12/58

MESSAGE:

Dr. Pais would like the Institute to pay for all of the reprints. Princeton University paid for the last order (A.P. and S.B.T.).

Also, Professor Treiman should receive 50 reprints.

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REQUISITION FOR PAYMENT

Date 20 June 1958

Pay to A. Pais

Address

Approved by (Signature) Verna Hobson Amount $ 4.50

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reimbursement of payment for
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Paid in Full

John H. Tomany
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DEPARTMENT OF PHYSICS

OK

June 21, 1957

Mrs. Hobson
Institute for Advanced Study
Princeton, New Jersey

Dear Mrs. Hobson:

We are enclosing two copies of our invoice for charges on the "Strong Coupling" article as per your agreement with our Mrs. Bolton. Please mail your check to the Physics Department (but make it payable to Columbia University).

Thank you.

Yours very truly,

I. Heneghan

I. Heneghan

W/R Serber
Phys Rev 105 1636-1652 (1957)

OK

Pais-Serber article "Strong Coupling" in Phys. Rev. reprint order send in by Columbia, who have ordered 200 for us (per Prof. Pais). They will bill us for 1/2 support of publication.

(tel. 1/28/57, Mrs. Bolton, Phys. Dept. Columbia)

rec'd Bldg E 2/22/57

3 sent to D.O.

Pais

C O P Y

COLUMBIA UNIVERSITY

IN THE CITY OF NEW YORK

OFFICE OF THE BURSAR

Date June 21, 1957

409

The Institute for Advanced Study
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To Columbia University, Dr.

150	Reprints of article "Strong Coupling" which appeared in the Physical Review of March 1, 1957	25.95
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VM

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Author: A. Pais and S. B. Treiman

Published in: THE PHYSICAL REVIEW 105, 5

Issue: March 1, 1957

Pages: 1616-1619

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arranged by telephone 1/30/57 with Miss Farleigh: split publication costs; 100 reprints for University; bill to IAS; we bill them.

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30 January 1957 ....
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700	28.10	40.90	60.50	90.90	105.50	126.60	154.00	182.90	197.80
750	28.90	42.50	63.00	95.00	110.40	132.30	161.30	191.80	207.50
800	29.70	44.10	65.40	99.00	115.20	138.00	168.60	200.70	217.20
850	30.40	45.60	67.60	102.70	119.60	143.10	175.20	208.70	225.90
900	31.10	47.00	69.80	106.30	123.90	148.20	181.70	216.70	234.50
950	31.80	48.50	72.00	110.00	128.30	153.30	188.30	224.70	243.20
1000	32.50	49.90	74.20	113.60	132.60	158.40	194.80	232.70	251.80
Additional 50's over 1000	.70	1.30	2.00	3.30	3.90	4.50	5.80	7.10	7.60

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19 April 1954

Dear Miss Alexander:

Herewith I submit to you for publication in the Proceedings of the National Academy of Sciences a manuscript by Dr. A. Pais entitled "On the Program of a Systematization of Particles and Interactions." The estimated length of this paper is about eight pages, plus one page of footnotes. Please bill Dr. A. Pais, Institute for Advanced Study, Princeton, N.J., for the space above the five-page limit. Would you also be good enough to correspond directly with him concerning all practical matters such as galley proofs and reprints.

Sincerely yours,

Robert Oppenheimer

Proceedings of the
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University of Chicago Press
5750 Ellis Avenue
Chicago 37, Illinois

Attention: Miss Mary D. Alexander

enclosure

Copy sent to Prof. Pais

Pais

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chg. Publications
11/30

Pais

The University of Chicago Press
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July 6, 1954

Mr. J. Robert Oppenheimer
The Institute for Advanced Study
Princeton, New Jersey

Dear Mr. Oppenheimer:

This will acknowledge with thanks receipt of the paper "Spherical spinors in a euclidean 4-space" by A. Pais. This paper is scheduled for publication in the September 1954 Proceedings of the National Academy of Sciences.

Sincerely yours,

Mary D Alexander

Mary D. Alexander
Production Editor

eh

Copy: Prof. Pais

29 June 1954

The Proceedings of the
National Academy of Sciences
University of Chicago Press
5750 Ellis Avenue
Chicago 37, Illinois
Attention: Miss Mary D. Alexander

Gentlemen:

I am submitting herewith a note by Professor A. Pais of the Institute for Advanced Study for publication in the Proceedings of the National Academy of Sciences. Further correspondence may be addressed to Professor Pais at this address.

Sincerely yours,

Robert Oppenheimer

enclosure

Merrie Mitchell called to say that she had been in touch with Prof. Pais, and he had asked if you would be willing to write a covering letter and send it to Merrie for mailing. (She has to add instructions to the printer).

File Pais ✓

PROGRESS OF THEORETICAL PHYSICS

Publication Office
Yukawa Hall, Kyoto University
Kyoto, Japan

No. A-277

Date: February 10, 1954

Ref:

In behalf of;

INVOICE

To:

Dr. A. Pais
The Institute for
Advanced Study
Princeton, N.J., U.S.A.

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Pais

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Dr Pais' ✓

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Date 15 Jan 54

Pay to Dr. W. J. Beekman, Treasurer

Address Foundation Physica, Bijlhouwerstraat 6, Utrecht, The Netherlands.

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Amount ~~$~~ Dutch Fl.178.64

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UTRECHT, December 9th, 1953.
Bijlhouwerstraat 6
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No. Ph-63

Rekening voor Mr A. Pais, Institute for Advanced Study,
PRINCETON. N.J. - U.S.A.

Pais, A. - Isotopic spin and mass quantization
(Physica, XIX, no. 9)

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October 23, 1952

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September 18, 1952

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Toward the cost of publication at $15.00 per page,

Article: Selection Rules Imposed by Charge Conjugation and Charge Symmetry.

Author: Pais and Jost

Published in: PHYSICAL REVIEW

Issue: September 1, 1952

Pages: 871 - 875

5 pages @ $15.00 per page $75.00

O.K. – Charge: Publications Fund
9/22/52
D.K.

X
Pais

August 27, 1952

Dear Miss Kelder:

Thank you for your letter of August 25th to Dr. Res Jost, which has come to my attention. Both Dr. Pais and Dr. Jost are abroad; and since they will not return to the Institute for some weeks, I am taking the liberty of handling the order for reprints.

The reprints order forms are usually sent in to the American Institute from our office. It may have been a slip up that none was sent in for the Pais-Jost paper. But without question, the order can be filled as stated by Dr. Pais. I am therefore sending the enclosed form which I have completed in their absence and with the approval of our office. I hope this will straighten out the matter.

Sincerely yours,

Katherine Russell
Secretary to the Director

Miss Diane M. Kelder
American Institute of Physics
57 East 55th St.
New York 22, N. Y.

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August 25, 1952

Mr. R. Jost
Institute for Advanced Study
Princeton University
Princeton, N.J.

Dear Sir:

With reference to your article "Selection Rules Imposed by Charge Conjugation and Charge Symmetry" appearing in the September 1st issue of the PHYSICAL REVIEW, we have received communication from Dr. Pais ordering 250 reprints (200 without and 50 with covers) and stating that the Institute at Princeton would pay the publication per page charge.

I am therefore enclosing order forms, as we have not yet received same from Dr. Pais. I should appreciate your returning them with the necessary information, which I am sure will corroborate Dr. Pais's Statement.

Thank you.

Very truly yours,

Diane M. Kelder

Diane M. Kelder

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PHYSICAL REVIEW

Issue September 1, 1952

Title of Article "Selection Rules Imposed by Charge Conjugation and Charge Symmetry"

Author A. Pais and R. Jost

I shall authorize the payment of $15.00 per page in support of the publication of this article. It is my understanding that 100 reprints without covers will be furnished free of charge to this institution.

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August 27, 1952
Date

Katherine Russell for A. Pais and R. Jost
Signature of Author

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Author: A. Pais

Published in: PHYSICAL REVIEW

Issue: June 1, 1952

Pages: 663 - 672

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Author: K. M. Case and A. Pais

Published in: THE PHYSICAL REVIEW

Issue: Oct. 15, 1950

Pages: 203-211

8.50 Pages @ $8.00 per page...... $68.00

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Article by Pais, et al in the July 1, 1950 issue: PHYSICAL REVIEW.

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"On Field Theories with Non-Localized Action"

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M. P.
Pais

5647

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Author: A. PAIS and G. E. Uhlenbeck

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Author: A. PAIS and G. E. UHLENBECK.

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May 8, 1950 — Date

A. Pais. — Signature of Author

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M 1.
Pais

February 9, 1950

The Editor
The Physical Review
University of Minnesota
Minneapolis, Minn.

Dear Sir:

We are sending you herewith a long manuscript by Pais and Uhlenbeck on "some fundamental problems in field theory". The eminence of the authors makes it unnecessary to vouch for the importance of the work; but I would like to assure you that the length of the article is indispensable if the subject is to be presented in the intelligible and definitive way that it deserves.

With every good wish,

Robert Oppenheimer

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Mr. Pais

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Dec. 5, 1949

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ATOMIC ENERGY COMMISSION

In Reply Refer To:
TIDRR:DEH 4-174

X Pais

Oak Ridge, Tennessee
April 25, 1951

original sent to Pais

Dr. N. H. Furman
Department of Chemistry
Princeton University
Princeton, New Jersey

Subject: REQUEST FOR REPORT

Dear Dr. Furman:

This office has received a request for a report entitled "Developments in the Theory of the Electron" by Abraham Pais, Princeton University (1948). 45 pp IAS/PU PU Press.

It would be appreciated if two copies could be furnished. If copies are not available for permanent retention, a loan copy would be sufficient for our needs. We would like permission to photostat a copy for permanent retention in our files. Distribution will be limited to official requesters within the Atomic Energy Commission.

Very truly yours,

ORIGINAL SIGNED BY
I. A. WARHEIT

I. A. Warheit, Chief
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Pais

21 December 1955

Dear Mr. Hill:

In answer to your enquiry of November 30th about PAIS (Abraham) Positron Theory, this is a paper which was published in Mat.-Fys. Med. of the Kgl. Danske Videnskabernes Selskad. We do not have here any reprints except for our file copy, but it may be that if you write to the magazine they could help you.

Proc. Copenhagen Academy

Sincerely yours,

(Mrs. Wilder Hobson)
Secretary to the Director

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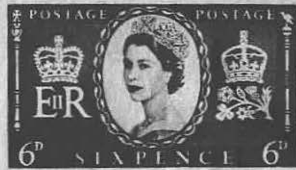

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30th November, 1955

Dear Sirs,

PAIS (Abraham) Positron theory.

We are trying to obtain full information on the above work, and we shall be most grateful if you will tell us whether it is still available, its publication date and price, and also send a prospectus or any other information you have which will help us to decide whether we wish to purchase it for our library.

Please do not send the book to us as we shall order it through our local bookseller if we require it.

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Yours faithfully,

R. H. Hill

Librarian.

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Reprinted from THE PHYSICAL REVIEW, Vol. 113, No. 3, 955–958, February 1, 1959
Printed in U. S. A.

A General Transformation of the Symmetrical Pseudoscalar Theory

A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

AND

R. SERBER,* *Department of Physics, Columbia University, New York, New York*

(Received October 1, 1958)

The symmetrical pseudoscalar theory with extended source is subjected to a rigorous transformation in such a way that the transformed Hamiltonian depends explicitly on the total isotopic spin and total angular momentum of the system. These collective variables are introduced by the same method of employing a general distribution function which was previously studied by the authors for the charged scalar theory.

I. INTRODUCTION

IN a preceding paper[1] the authors have shown how certain symmetries possessed by a field theory can be explicitly expressed in terms of appropriate collective variables through the introduction into the Hamiltonian and the commutation relations of a distribution function f. In first instance f is arbitrary, so that a way is opened for the application of variational methods, namely by minimizing a suitably chosen leading part of the Hamiltonian with respect to f. As an illustration, the scalar charged meson theory was considered, and it was shown how a particular choice of the distribution function led to the usual strong-coupling treatment. In the present paper we develop the formalism for the symmetrical pseudoscalar meson theory. Our treatment resembles that of Pauli and Dancoff,[2] but is more general in that these authors make a particular choice of distribution function, and more exact in that no terms are dropped in the present derivation. The final form in which the dynamics is cast in this paper is given by Eqs. (46)–(49) below. In the rigorous expression for the Hamiltonian, Eq. (49), the total isotopic spin and the total angular momentum appear explicitly. While the extreme strong-coupling approach becomes immediately obvious for a particular choice of f, there is nothing in these equations that confines the formalism necessarily to this rather unrealistic regime. We believe that this generality and exactness will prove of value in the further development of the theory, to which recent experimental indications have lent added interest.[3]

II. TRANSFORMATION OF THE HAMILTONIAN

We start from the outset with one nucleon treated as a static extended source $U(x)$, so the Hamiltonian is

$$H=H_{\text{mes}}+H_{\text{int}}, \tag{1}$$

$$H_{\text{mes}}=\tfrac{1}{2}\sum_{\alpha}\int(\pi_\alpha^2+\varphi_\alpha\omega^2\varphi_\alpha)d\mathbf{x}, \tag{2}$$

$$H_{\text{int}}=\frac{g(2\pi)^{\frac{1}{2}}}{\kappa}\sum_{\alpha,k}\tau_\alpha\sigma_k\int\frac{\partial U}{\partial x_k}\varphi_\alpha d\mathbf{x}, \tag{3}$$

where κ is the meson mass (in units $\hbar=c=1$). Summations over α and k are from 1 to 3. The 3-field corresponds to neutral mesons. σ_k is the nucleon spin. The meson field commutation relations are given by ($\hbar=1$)

$$[\pi_\alpha(\mathbf{x},t),\varphi_\beta(\mathbf{x}',t)]=-i\delta_{\alpha\beta}\delta(\mathbf{x}-\mathbf{x}').$$

The operator T_α^0 of isotopic angular momentum is

$$T_\alpha^0=t_\alpha+\tfrac{1}{2}\tau_\alpha,$$
$$t_1=\int(\varphi_2\pi_3-\varphi_3\pi_2)d\mathbf{x},\quad\text{cycl.} \tag{4}$$

The operator J_k^0 of angular momentum is

$$J_k^0=l_k+\tfrac{1}{2}\sigma_k,$$
$$l_1=-\sum_\alpha\int\pi_\alpha\left(x_2\frac{\partial}{\partial x_3}-x_3\frac{\partial}{\partial x_2}\right)\varphi_\alpha d\mathbf{x},\quad\text{cycl.} \tag{5}$$

In analogy to our procedure for the charged scalar case,[1] we put

$$\varphi_\alpha=\varphi_\alpha'+F^{-\frac{1}{2}}\sum_k Q_{\alpha k}\frac{\partial f}{\partial x_k},$$
$$\pi_\alpha=\pi_\alpha'+F^{-\frac{1}{2}}\sum_k P_{\alpha k}\frac{\partial f}{\partial x_k}, \tag{6}$$

where f is the variational function of the problem. It is provisionally left arbitrary apart from one restriction:

$$f \text{ is a spherically symmetric function of } \mathbf{x}. \tag{7}$$

The $P_{\alpha k}$, $Q_{\alpha k}$ are defined by

$$P_{\alpha k}=F^{-\frac{1}{2}}\int\frac{\partial f}{\partial x_k}\pi_\alpha d\mathbf{x},\quad Q_{\alpha k}=F^{-\frac{1}{2}}\int\frac{\partial f}{\partial x_k}\varphi_\alpha d\mathbf{x}. \tag{8}$$

As a consequence of condition (7), the P's and Q's are canonical in the sense that

$$[P_{\alpha k},Q_{\beta l}]=-i\delta_{\alpha\beta}\delta_{kl}, \tag{9}$$

provided F is chosen to be

$$F=\tfrac{1}{3}\int(\nabla f)^2d\mathbf{x}. \tag{10}$$

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[1] A. Pais and R. Serber, Phys. Rev. **105**, 1636 (1957).
[2] W. Pauli and S. M. Dancoff, Phys. Rev. **62**, 85 (1942).
[3] See L. Landovitz and B. Margolis, Phys. Rev. Letters **1**, 206 (1958).

We further note the following commutation and orthogonality relations:

$$[\pi_\alpha'(\mathbf{x},t),\phi_\beta'(\mathbf{x}',t)]$$
$$=-i\delta_{\alpha\beta}\left[\delta(\mathbf{x}-\mathbf{x}')-F^{-1}\sum_k\frac{\partial f(x)}{\partial x_k}\frac{\partial f(x')}{\partial x_k'}\right], \quad (11)$$

$$[P_{\alpha k},\varphi_\beta']=[\pi_\alpha',Q_{\beta k}]=0, \quad (12)$$

$$\int\varphi_\alpha'\frac{\partial f}{\partial x_k}d\mathbf{x}=\int\pi_\alpha'\frac{\partial f}{\partial x_k}d\mathbf{x}=0. \quad (13)$$

Substitution of Eq. (6) in Eq. (1) gives

$$H=H_{\mathrm{mes}}'+H_{\mathrm{int}}'+\sum_{\alpha,k}\left[\tfrac{1}{2}P_{\alpha k}^2+\tfrac{1}{2}\Omega^2Q_{\alpha k}^2\right.$$
$$\left.+F^{-\frac{1}{2}}Q_{\alpha k}\int\varphi_\alpha'\omega^2\frac{\partial f}{\partial x_k}d\mathbf{x}+\frac{g(2\pi)^{\frac{1}{2}}}{\kappa}bQ_{\alpha k}\tau_\alpha\sigma_k\right], \quad (14)$$

$$\Omega^2=\tfrac{1}{3}F^{-1}\int(\nabla f)\cdot\omega^2\nabla f d\mathbf{x},\quad b=\tfrac{1}{3}F^{-\frac{1}{2}}\int\nabla U\cdot\nabla f d\mathbf{x}, \quad (15)$$

while T_α^0, J_k^0 become

$$T_\alpha^0=t_\alpha'+\tfrac{1}{2}\tau_\alpha+I_\alpha^0, \quad (16)$$
$$I_1^0=\textstyle\sum_k(Q_{2k}P_{3k}-Q_{3k}P_{2k}),\quad \text{cycl.}, \quad (17)$$
$$J_\alpha^0=l_\alpha'+\tfrac{1}{2}\sigma_\alpha+L_\alpha^0, \quad (18)$$
$$L_1^0=\textstyle\sum_k(Q_{k2}P_{k3}-Q_{k3}P_{k2}),\quad \text{cycl.} \quad (19)$$

Note that

$$[t_1',t_2']=it_3';\quad [l_1',l_2']=il_3', \quad (20)$$

even though the π', φ' do not satisfy the usual commutation relations. The orthogonality relations (13) make up for this, while for the l_k'-relations the condition (7) has also been made use of. Further, we obviously have that

$$[I_1^0,I_2^0]=iI_3^0;\quad [L_1^0,L_2^0]=iL_3^0;\quad \text{cycl.} \quad (21)$$

Following Pauli and Dancoff,[2] we next transform the nine collective coordinates $Q_{\alpha k}$ into a set of three angular variables in space, a similar set in isotopic space, and three radial variables. Considering the angles in space, one can introduce the usual orthogonal matrix (call it A_{kl}) that corresponds to the solid rotation described by these angles. Likewise one introduces an orthogonal matrix $B_{\alpha\beta}$ for the isotopic variables. The transformation from the variables $Q_{\alpha k}$ to the rotated set $q_{\alpha k}$, is of the form

$$Q_{\alpha k}=\textstyle\sum_{sr}B_{r\alpha}A_{sk}q_{rs}.$$

The defining condition for the transformation in question is that it be a principal axis transformation, that is, that $q_{rs}=q_r\delta_{rs}$.

$$Q_{\alpha k}=\textstyle\sum_r B_{r\alpha}A_{rk}q_r. \quad (22)$$

The corresponding transformation for the momenta is

$$P_{\alpha k}=\textstyle\sum_{sr}B_{r\alpha}A_{sk}p_{rs}. \quad (23)$$

The problem of expressing the p_{rs} in terms of canonical variables has been treated by Pauli and Dancoff, and we need state only the result. This is expressed in terms of the quantities

$$I_\alpha=\textstyle\sum_\beta B_{\alpha\beta}I_\beta^0,\quad L_k=\sum_j A_{kj}L_j^0; \quad (24)$$

which are the components of the isotopic and angular momenta in the directions of the rotating system of axes. The properties of these variables are well known from the theory of tops,[4] and can be readily derived if one notes that, since $B_{\alpha\beta}$ (for fixed α) transforms like a vector under rotations, its commutation relations with I_β^0 are[5]

$$[B_{\alpha\beta},I_{\beta'}^0]=iB_{\alpha\beta''},\quad (\beta,\beta',\beta''\text{ cyclic}). \quad (25)$$

It then follows immediately from (24) that the I_α satisfy the anomalous commutation relations

$$[I_\alpha,I_{\alpha'}]=-iI_{\alpha''}\quad (\alpha,\alpha',\alpha''\text{ cyclic}), \quad (26)$$

while the I_α and I_β^0 commute:

$$[I_\alpha,I_\beta^0]=0. \quad (27)$$

From (27) and the orthogonality of the B matrix, one verifies that

$$\textstyle\sum_\alpha I_\alpha^2=\sum_\beta I_\beta^{02}. \quad (28)$$

$B_{\alpha\beta}$ and I_α satisfy the commutation relations

$$[B_{\alpha\beta},I_{\alpha'}]=-iB_{\alpha''\beta}\quad (\alpha,\alpha',\alpha''\text{ cyclic}). \quad (29)$$

It is sometimes convenient to introduce the notation

$$I_\alpha\equiv I_{\alpha'\alpha''},\quad (\alpha,\alpha',\alpha''\text{ cyclic}). \quad (30)$$

The momenta p_{rs} then take the form

$$p_{rs}=p_r\delta_{rs}+\frac{1}{2}\frac{(L_{rs}+I_{rs})}{q_r-q_s}+\frac{1}{2}\frac{(L_{rs}-I_{rs})}{q_r+q_s}, \quad (31)$$

where p_r is canonically conjugate to q_r.

The angular momenta can be expressed in terms of the rotated variables by

$$I_{rr'}=\textstyle\sum_s(q_{rs}p_{r's}-q_{r's}p_{rs})=q_rp_{r'r}-q_{r'}p_{rr'},$$
$$L_{rr'}=\textstyle\sum_s(q_{sr}p_{sr'}-q_{sr'}p_{sr})=q_rp_{rr'}-q_{r'}p_{r'r}.$$

It may be remarked that

$$I_{rs}+L_{rs}=0\quad\text{when}\quad q_r=q_s. \quad (32)$$

This is the analog, in the present problem, of the familiar relation that the angular momentum is zero if the radial coordinate vanishes.

The kinetic energy can be expressed in terms of the

[4] See J. H. Van Vleck, Revs. Modern Phys. 23, 213 (1951).

[5] Exactly analogous relations hold for A_{jk}, L_m^0. Since the relations in both spaces are identical, we shall only write out one set.

new variables by using Eqs. (23), (31), and (29). One finds

$$\tfrac{1}{2}\sum_{\alpha k} P_{\alpha k}{}^2=\tfrac{1}{2}\sum_r p_r{}^2+\tfrac{1}{8}\sum_{r,s}\left[\frac{(I_{rs}+L_{rs})^2}{(q_r-q_s)^2}+\frac{(I_{rs}-L_{rs})^2}{(q_r+q_s)^2}\right]$$
$$-\frac{i}{2}\sum_{r,s}\frac{1}{q_r{}^2-q_s{}^2}(q_rp_r-q_sp_s). \quad (33)$$

The appearance of a term linear in the momenta of course means that a weight factor (the part of the volume element depending on the q_r) has been introduced by our transformation of variables. The weight factor, g, can be determined by writing the radial part of the kinetic energy operator (leaving out the centrifugal potential terms) in the form

$$-\tfrac{1}{2}\sum_r \frac{1}{g}\frac{\partial}{\partial q_r}g\frac{\partial}{\partial q_r}.$$

One finds

$$g=(q_1{}^2-q_2{}^2)(q_1{}^2-q_3{}^2)(q_2{}^2-q_3{}^2). \quad (34)$$

This weight factor vanishes when two of the q_r's are equal, and its form makes evident an ambiguity in our definition of variables which can be removed by an ordering convention, e.g.,

$$q_1{}^2\geq q_2{}^2\geq q_3{}^2. \quad (35)$$

Furthermore, bearing in mind that the matrices A, B in Eq. (22) have determinant $+1$, one sees that it is possible to choose $q_1\geq q_2\geq 0$.

The weight factor can be eliminated in the usual manner by changing the state vector by the relation

$$\Phi=\Phi'/g^{\frac{1}{2}}. \quad (36)$$

The Hamiltonian, considered to act on Φ', is then

$$H=H_{\text{mes}}'+H_{\text{int}}'$$
$$+\frac{1}{2}\left[\sum_r p_r{}^2+\tfrac{1}{4}\sum_{r,s}\left(\frac{(I_{rs}+L_{rs})^2-1}{(q_r-q_s)^2}+\frac{(I_{rs}-L_{rs})^2-1}{(q_r+q_s)^2}\right)\right]$$
$$+\tfrac{1}{2}\Omega^2\sum_r q_r{}^2+F^{-\frac{1}{2}}\sum_{\alpha,k,r}q_rB_{r\alpha}A_{kr}\int\varphi_\alpha'\omega^2\frac{\partial f}{\partial x_k}d\mathbf{x}$$
$$+\frac{g(2\pi)^{\frac{1}{2}}}{\kappa}b\sum_{\alpha,k,r}q_rB_{r\alpha}A_{kr}\tau_\alpha\sigma_k. \quad (37)$$

The (-1)'s in the centrifugal potential terms result from the transformation (36).

Next we apply to H a canonical transformation S such that the angular variables contained in A and B no longer occur explicitly in the Hamiltonian. Put $S=S_\tau S_\sigma$. Then S_τ should be such that

$$S_\tau X_\alpha S_\tau{}^{-1}=\textstyle\sum_\beta B_{\beta\alpha}X_\beta, \quad (38)$$

where X_α stands for τ_α or φ_α' or π_α', while

$$S_\sigma Y_k S_\sigma{}^{-1}=\textstyle\sum_l A_{lk}Y_l, \quad (39)$$

where Y_k stands for σ_k or x_k. The explicit form of S is given in the appendix; there it is also shown that

$$\begin{aligned} SI_\alpha{}^0S^{-1}&=I_\alpha{}^0-\textstyle\sum_\beta B_{\beta\alpha}(t_\beta'+\tfrac{1}{2}\tau_\beta),\\ SL_k{}^0S^{-1}&=L_k{}^0-\textstyle\sum_m A_{mk}(l_m'+\tfrac{1}{2}\sigma_m).\end{aligned} \quad (40)$$

Hence from Eqs. (16), (18), (38), and (39):

$$ST_\alpha{}^0S^{-1}=I_\alpha{}^0;\quad SI_k{}^0S^{-1}=L_k{}^0. \quad (41)$$

Furthermore we see from Eqs. (24) and (40) that

$$\begin{aligned} SI_\alpha S^{-1}&=I_\alpha-t_\alpha'-\tfrac{1}{2}\tau_\alpha,\\ SL_kS^{-1}&=L_k-l_k'-\tfrac{1}{2}\sigma_k.\end{aligned} \quad (42)$$

By taking the S transform of the commutation relations (26), it follows from (42) that $I_\alpha-t_\alpha'-\frac{1}{2}\tau_\alpha$ satisfies anomalous commutation relations. This is in accordance with the anomalous relations that hold for I_α itself and with the normal relations that hold for t_α' and for $\frac{1}{2}\tau_\alpha$. [Note from Eqs. (12) and (24) that I_α commutes with t_α'.] An entirely similar situation obtains for $L_k-l_k'-\frac{1}{2}\sigma_k$.

It follows from (41) that the components of isotopic and angular momenta in the directions of the rotating axes, T_β and J_k [which are related to $T_\beta{}^0$, $J_k{}^0$ by the analogs of (24)] transform according to

$$ST_\alpha S^{-1}=I_\alpha;\quad SJ_kS^{-1}=L_k. \quad (43)$$

The relations (41), (43) show that the new variables $I_\alpha{}^0$, I_α represent the components of the total isotopic spin vector along the axes of the fixed and rotating systems, respectively. They have the properties described by Eqs. (21) and (25) to (29). Similarly $L_\alpha{}^0$, L_α represent the total angular momenta. The total isotopic spin and angular momenta are, of course, half-integer quantized.

Applying the S transformation to the Hamiltonian (37) we get

$$H=H_{\text{mes}}'+H_{\text{int}}'+\frac{g(2\pi)^{\frac{1}{2}}}{\kappa}b\sum_r q_r\sigma_r\tau_r$$
$$+\tfrac{1}{2}\sum_r(p_r{}^2+\Omega^2q_r{}^2)+F^{-\frac{1}{2}}\sum_r q_r\int\varphi_r'\omega^2\frac{\partial f}{\partial x_r}d\mathbf{x}$$
$$+\tfrac{1}{8}\sum_{r,s}\left[\frac{[(I_{rs}-t_{rs}'-\frac{1}{2}\tau_{rs})+(L_{rs}-l_{rs}'-\frac{1}{2}\sigma_{rs})]^2-1}{(q_r-q_s)^2}\right.$$
$$\left.+\frac{[(I_{rs}-t_{rs}'-\frac{1}{2}\tau_{rs})-(L_{rs}-l_{rs}'-\frac{1}{2}\sigma_{rs})]^2-1}{(q_r+q_s)^2}\right]. \quad (44)$$

We recall that the commutation and orthogonality relations for the meson fields are given by Eqs. (11) and (13) and that the form of t_{rs}' and l_{rs}' is given in Eqs. (4) and (5).

As in the scalar theory, it is possible to eliminate entirely the radial oscillator variables p_r, q_r from the Hamiltonian (44): define new meson variables π_α'', φ_α'' by

$$\pi_\alpha''=\pi_\alpha'+F^{-\frac{1}{2}}p_\alpha\frac{\partial f}{\partial x_\alpha},$$
$$\varphi_\alpha''=\varphi_\alpha'+F^{-\frac{1}{2}}q_\alpha\frac{\partial f}{\partial x_\alpha}. \tag{45}$$

Note that no summation over α is implied in the second term on the right. Upon using the orthogonality relations (13), it follows that

$$q_\alpha=F^{-\frac{1}{2}}\int\varphi_\alpha''\frac{\partial f}{\partial x_\alpha}d\mathbf{x}. \tag{46}$$

The commutation relations are

$$[\pi_\alpha''(\mathbf{x},t),\varphi_\beta''(\mathbf{x}',t)]$$
$$=-i\delta_{\alpha\beta}\left[\delta(\mathbf{x}-\mathbf{x}')-F^{-1}\sum_k{}'\frac{\partial f(x)}{\partial x_k}\frac{\partial f(x')}{\partial x_k'}\right], \tag{47}$$

where the prime on the summation over k means that the term $k=\alpha$ is to be excluded. Instead of the orthogonality relations (13), we now have

$$\int\varphi_\alpha''\frac{\partial f}{\partial x_\beta}d\mathbf{x}=\int\pi_\alpha''\frac{\partial f}{\partial x_\beta}d\mathbf{x}=0,\quad \alpha\neq\beta. \tag{48}$$

As a result t_{rs}'', l_{rs}'' still satisfy commutation relations of the type (20).

In terms of the double-primed variables, H becomes

$$H=H_{\text{mes}}''+H_{\text{int}}''$$
$$+\frac{1}{8}\sum_{r,s}\left[\frac{[(I_{rs}-t_{rs}''-\frac{1}{2}\tau_{rs})+(L_{rs}-l_{rs}''-\frac{1}{2}\sigma_{rs})]^2-1}{(q_r-q_s)^2}\right.$$
$$\left.+\frac{[(I_{rs}-t_{rs}''-\frac{1}{2}\tau_{rs})-(L_{rs}-l_{rs}''-\frac{1}{2}\sigma_{rs})]^2-1}{(q_r+q_s)^2}\right]. \tag{49}$$

No approximations whatsoever have been made in the derivation of Eq. (49). In the usual strong-coupling treatment a particular choice of the distribution function f is made: the choice $f=U$, which, in virtue of (48), diagonalizes H_{int}''. In comparing (49) with the corresponding expression given by Pauli and Dancoff, it should be remembered that these authors dropped terms, in the course of their calculations, which were inessential for their purposes. Thus they omitted the contributions of free mesons both in the numerators and denominators of the centrifugal potential terms, and also the (-1)'s in the numerators. This is in the spirit of a quasi-classically determined self-field: in the classical theory a particular solution is obtained in which the free meson fields are exactly zero. Nor are the (-1)'s, arising from the transformation (36), present in the classical treatment.[6]

APPENDIX

The S Transformation

We wish to construct $S=S_\tau S_\sigma$ such that the relations (38), (39) hold true. We give the derivation of S_τ; S_σ is found in an entirely similar way.

For this purpose it is easiest to write down $B_{\alpha\beta}$ explicitly in terms of Euler angles θ, φ, ψ:

$$B_{\alpha\beta}=\begin{pmatrix}\cos\theta\cos\varphi\cos\psi-\sin\varphi\sin\psi & \cos\theta\sin\varphi\cos\psi+\cos\varphi\sin\psi & -\sin\theta\cos\psi\\ -\cos\theta\cos\varphi\sin\psi-\sin\varphi\cos\psi & -\cos\theta\sin\varphi\sin\psi+\cos\varphi\cos\psi & \sin\theta\sin\psi\\ \sin\theta\cos\varphi & \sin\theta\sin\varphi & \cos\theta\end{pmatrix}.$$

Introducing the abbreviation

$$y_\alpha=t_\alpha'+\tfrac{1}{2}\tau_\alpha,$$

one readily verifies that the desired S_τ is given by

$$S_\tau=e^{iy_3\psi}e^{iy_2\theta}e^{iy_3\varphi}.$$

Denote by P_θ the conjugate to θ, etc. Then

$$I_1^0=-\sin\varphi P_\theta+\frac{\cos\varphi}{\sin\theta}(P_\psi-\cos\theta P_\varphi),$$
$$I_2^0=\cos\varphi P_\theta+\frac{\sin\varphi}{\sin\theta}(P_\psi-\cos\theta P_\varphi),$$
$$I_3^0=P_\varphi.$$

Now

$$SP_\theta S^{-1}=P_\theta-(y_1\sin\psi+y_2\cos\psi),$$
$$SP_\varphi S^{-1}=P_\varphi-(-y_1\sin\theta\cos\psi+y_2\sin\theta\sin\psi+y_3\cos\theta),$$
$$SP_\psi S^{-1}=P_\psi-y_3.$$

From these relations one immediately obtains the first of Eqs. (40).

[6] It may be pointed out that in the WKB treatment of the radial Schrödinger equation it is also necessary to add a fictitious centrifugal potential $1/(4r^2)$ which changes $l(l+1)$ to $(l+\frac{1}{2})^2$. A similar argument, based on the WKB approximation, applies in the present case.