

Representations of the Poincaré group for relativistic extended hadrons

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(Received 7 June 1978; revised manuscript received 23 October 1978)

Representations of the Poincaré group are constructed from the relativistic harmonic oscillator wave functions which have been effective in describing the physics of internal quark motions in the relativistic quark model. These wave functions are solutions of the Lorentz-invariant harmonic oscillator differential equation in the "cylindrical" coordinate system moving with the hadronic velocity in which the time-separation variable is treated separately. This result enables us to assert that the hadronic mass spectrum is generated by the internal quark level excitation, and that the hadronic spin is due to the internal orbital angular momentum. An addendum relegated to PAPS contains discussions of detailed calculational aspects of the Lorentz transformation, and of solutions of the oscillator equation which are diagonal in the Casimir operators of the homogeneous Lorentz group. It is shown there that the representation of the homogeneous Lorentz group consists of solutions of the oscillator partial differential equation in a "spherical" coordinate system in which the Lorentz-invariant Minkowskian distance between the constituent quarks is the radial variable.

I. INTRODUCTION

In building models of relativistic extended hadrons, we have to keep in mind the fundamental fact that the overall space-time symmetry structure is that of the Poincaré group.¹ In our previous papers on physical applications of the relativistic harmonic oscillator,² our primary purpose was to devise a calculational scheme for explaining experimental observations. As was pointed out by Biedenharn *et al.*,³ the question of the Poincaré symmetry has not been systematically discussed.

The purpose of the present paper is to address this symmetry problem. We are considering a model hadron consisting of two spinless quarks bound together by a harmonic oscillator potential. In this case, we are led to consider the center-of-mass coordinate which specifies the space-time location of the hadron, and the relative coordinate which specifies the internal space-time separation between the quarks.

Both the hadronic and internal coordinates are subject to Poincaré transformations consisting of translations and Lorentz transformations. The hadronic coordinate undergoes Poincaré transformation in the usual manner. However, the internal coordinate is invariant under translations. This coordinate should, nonetheless, satisfy the Poincaré symmetry as a whole. We discuss in this paper the role of this internal coordinate, and show that internal excitations generate the hadronic mass spectrum, and that the internal angular momentum corresponds to the spin of the hadron.

In Sec. II, we formulate the problem using a model hadron consisting of two spinless quarks bound together by a

harmonic oscillator potential of unit strength, and then discuss the generators of the Poincaré group applicable to the entire system. In Sec. III, we present the oscillator wave functions which are diagonal in the invariant Casimir operators of the Poincaré group.

II. FORMULATION OF THE PROBLEM

In our previous papers on physical applications of the relativistic harmonic oscillators, we started with the following Lorentz-invariant differential equation:

$$\{2[\square_1 + \square_2] - \frac{1}{16}(x_1 - x_2)^2 + m_0^2\}\phi(x_1, x_2) = 0, \quad (1)$$

where x_1 and x_2 are the space-time coordinates for the two spinless quarks bound together by a harmonic oscillator potential with unit spring constant. In order to simplify the above equation, let us define new coordinate variables

$$X = \frac{1}{2}(x_1 + x_2), \quad x = (1/2\sqrt{2})(x_1 - x_2). \quad (2)$$

The X coordinate represents the space-time specification of the hadron as a whole, while the x variable measures the relative space-time separation between the quarks. In terms of these variables, Eq. (1) can be written as

$$\left[\frac{\partial^2}{\partial X_\mu^2} + m_0^2 + \frac{1}{2} \left(\frac{\partial^2}{\partial x_\mu^2} - x_\mu^2 \right) \right] \phi(X, x) = 0. \quad (3)$$

The above equation is separable in the X and x variables. Thus we write

$$\phi(X, x) = f(X)\psi(x), \quad (4)$$

where $f(X)$ and $\psi(x)$ satisfy the following differential equations respectively:

$$\left[\frac{\partial^2}{\partial X_\mu^2} + m_s^2 + (\lambda + 1) \right] f(X) = 0, \quad (5)$$

$$\frac{1}{2} \left(\frac{\partial^2}{\partial x_\mu^2} - x_\mu^2 \right) \psi(x) = (\lambda + 1) \psi(x). \quad (6)$$

The differential equation of Eq. (5) is a Klein-Gordon equation, and its solutions are well known. $f(X)$ takes the form

$$f(X) = \exp(\pm ip \cdot X), \quad (7)$$

with

$$p^2 = m_s^2 + (\lambda + 1), \quad (8)$$

where p is the 4-momentum of the hadron. p^2 is, of course, the mass of the hadron and is numerically constrained to take the values allowed by Eq. (8). The separation constant λ is determined from the solutions of the harmonic oscillator differential equation of Eq. (6). The physical solutions of the oscillator equation satisfy the subsidiary condition

$$p^\mu a_\mu^\dagger \psi_\beta(x) = 0, \quad (9)$$

where

$$a_\mu^\dagger = x_\mu + \frac{\partial}{\partial x^\mu}$$

The physics of this subsidiary condition has been extensively discussed in the literature.^{1,2}

The space-time transformation of the total wave function of Eq. (4) is generated by the following ten generators of the Poincaré group. The operators

$$P_\mu = i \frac{\partial}{\partial X^\mu} \quad (10)$$

generate space-time translations. Lorentz transformations, which include boosts and rotations, are generated by

$$M_{\mu\nu} = L_{\mu\nu}^* + L_{\mu\nu}, \quad (11)$$

where

$$L_{\mu\nu}^* = i \left(X_\mu \frac{\partial}{\partial X^\nu} - X_\nu \frac{\partial}{\partial X^\mu} \right),$$

$$L_{\mu\nu} = i \left(x_\mu \frac{\partial}{\partial x^\nu} - x_\nu \frac{\partial}{\partial x^\mu} \right).$$

The translation operators P_μ act only on the hadronic coordinate, and do not affect the internal coordinate. The operators $L_{\mu\nu}^*$ and $L_{\mu\nu}$ Lorentz-transform the hadronic and internal coordinates respectively. The above ten generators satisfy the commutation relations for the Poincaré group.

In order to consider irreducible representations of the Poincaré group, we have to construct wave functions which are diagonal in the invariant Casimir operators of the group, which commute with all the generators of Eqs. (10) and (11). The Casimir operators in this case are

$$P^\mu P_\mu \quad \text{and} \quad W^\mu W_\mu, \quad (12)$$

where

$$W_\mu = \epsilon_{\mu\nu\alpha\beta} P^\nu M^{\alpha\beta}.$$

The eigenvalues of the above P^2 and W^2 represent respectively the mass and spin of the hadron.

III. PHYSICAL WAVE FUNCTIONS AND REPRESENTATIONS OF THE POINCARÉ GROUP

In constructing wave functions diagonal in the Casimir operators of the Poincaré group, we note first that the operator which acts on the wave function in the subsidiary condition of Eq. (9) commutes with these invariant operators:

$$[P^2, p^\mu a_\mu^\dagger] = 0, \quad (13)$$

$$[W^2, p^\mu a_\mu^\dagger] = 0. \quad (14)$$

Therefore, the wave functions satisfying the condition of Eq. (9) can be diagonal in the Casimir operators.

In order to obtain the solutions explicitly, let us assume without loss of generality that the hadron moves along the z direction with the velocity parameter β . Then we are led to consider the Lorentz frame where the hadron is at rest, and the coordinate variables are given by

$$\begin{aligned} x' &= x, & y' &= y, \\ z' &= (z - \beta t)/(1 - \beta^2)^{1/2}, \\ t' &= (t - \beta z)/(1 - \beta^2)^{1/2}. \end{aligned} \quad (15)$$

The Lorentz-invariant oscillator equation of Eq. (6) is separable in the above variables. In terms of these primed variables, we can construct a complete set of wave functions

$$\psi_\beta(x) = f_b(x') f_s(y') f_n(z') f_k(t'), \quad (16)$$

where

$$f_n(z') = (\sqrt{\pi} 2^n n!)^{-1/2} H_n(z') \exp(-z'^2/2),$$

$$f_k(t') = (\sqrt{\pi} 2^k k!)^{-1/2} H_k(t') \exp(-t'^2/2).$$

If the excitation numbers, b, \dots, k are allowed to take all possible nonnegative integer values, the solutions in Eq. (16) form a complete set. However, the eigenvalue λ takes the form

$$\lambda = b + s + n - k. \quad (17)$$

Because the coefficient of k is negative in the above expression, λ has no lower bound, and there is an infinite degeneracy for a given value of λ .

In terms of the primed coordinates, the subsidiary condition of Eq. (9) takes the simple form

$$\left(\frac{\partial}{\partial t'} + t' \right) \psi_\beta(x) = 0. \quad (18)$$

This limits $f_k(t')$ to $f_n(t')$, and the eigenvalue λ becomes

$$\lambda = b + s + n, \quad (19)$$

The physical wave functions satisfying the subsidiary condition of Eq. (9) or (18) have nonnegative values of λ .

As far as the x', y', z' coordinates are concerned, they form an orthogonal Euclidean space, and $f_b(x'), f_s(y'), f_n(z')$ form a complete set in this three-dimensional space. The Hermite polynomials in these Cartesian wave functions can then be combined to form the eigenfunctions of W^2 which, in terms of the primed coordinate variables, takes the form

$$W^2 = M^2(\mathbf{L}')^2, \quad (20)$$

where

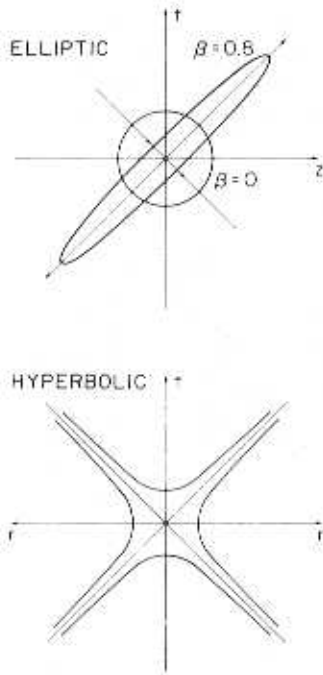


FIG. 1. Elliptic and hyperbolic localizations in space-time. The wave functions in the present paper are elliptically localized, and undergo Lorentz deformation as the hadron moves. The Lorentz invariant form $x^\mu x_\mu$, to which we are accustomed, is hyperbolically localized, and is basically different from the form used in the present paper.

$$L'_i = -i\epsilon_{ijk}x'_j \frac{\partial}{\partial x'_k},$$

and M is the hadronic mass.

The physical wave functions now take the form

$$\psi_{\beta}^{l'm}(x) = (1/\pi)^{3/4} [\exp(-t'^2)] R_{\lambda l}(r') Y_{lm}(\theta', \phi'), \quad (21)$$

where r', θ', ϕ' are the radial and spherical variables in the three-dimensional space spanned by x', y', z' . $R_{\lambda l}(r')$ is the normalized radial wave function for the three-dimensional isotropic harmonic oscillator, and its form is well known. The above wave function is diagonal in W^2 for which the eigenvalue is $l(l+1)M^2$, and l represents the total spin of the hadron in the present case. The quantum number m corresponds to the helicity.

Since the eigenvalue p^2 of the Casimir operator P^2 is constrained to take the numerical values allowed by Eq. (8), the hadronic mass is given by

$$M^2 = m_0^2 + (\lambda + 1). \quad (22)$$

If we relax the subsidiary condition of Eq. (18), we indeed obtain a complete set. In this case, λ of Eq. (17) can become negative for sufficiently large values of k . For $\lambda > 0$, the solutions become

$$\begin{aligned} \psi_{\beta}^{l'mk}(x) = & \left[\sqrt{\frac{\pi}{2}} 2^k k! \right]^{-1/2} H_k(t') [\exp(-t'^2/2)] \\ & \times R_{\lambda+k, l}(r') Y_{lm}(\theta', \phi'). \end{aligned} \quad (23)$$

For $\lambda < 0$, the solutions take the form

$$\begin{aligned} \psi_{\beta}^{l'mk}(x) = & \left[\sqrt{\frac{\pi}{2}} 2^{k-\lambda} (k-\lambda)! \right]^{-1/2} H_{k-\lambda}(t') \\ & \times [\exp(-t'^2)] R_{k, l}(r') Y_{lm}(\theta', \phi'). \end{aligned} \quad (24)$$

The eigenvalues of P^2 and W^2 are again $m_0^2 + (\lambda + 1)$ and $l(l+1)M^2$ respectively. In both of the above cases, k is allowed to take all possible integer values.

The functional forms of Eqs. (23) and (24) are relatively simple, and they suggest that this representation of the Poincaré group corresponds to the solution of the Lorentz-invariant oscillator differential equation in a "cylindrical" coordinate system moving with the hadronic velocity where the t' variable is treated separately. We are then led to the question of why this fact was not known.

Even though the above representations take simple forms, the wave functions contain the following nonconventional features. The first point to note is that they are written as functions of the x', y', z', t' variables. The transverse variables x', y' are simply x and y respectively. However, z' and t' are linear combinations of z and t . Because the physical meaning of the time-separation variable was not clearly understood, the t dependence discouraged us in the past from using it explicitly in representation theory. The explicit use of this variable in the present paper is based on the progress that has been made in our physical understanding of this time-separation variable in terms of measurable quantities, and in terms of the relativistic wave functions carrying a covariant probability interpretation.⁷

Another factor which used to discourage the use of the t variable was that we are accustomed to its appearance through the form

$$x^\mu x_\mu = t^2 - r^2, \quad (25)$$

where

$$r^2 = x^2 + y^2 + z^2.$$

In terms of this form, it is very inconvenient, if not impossible, to describe functions which are localized in a finite space-time region.

In contrast to the above hyperbolic case, the wave functions which we constructed in this paper are well localized within the region

$$(z'^2 + t'^2) < 2, \quad (26)$$

due to the Gaussian factor appearing in the wave functions. This elliptic form was obtained from the covariant expression

$$-x^\mu x_\mu + 2(x \cdot p/M)^2 = x^2 + y^2 + z^2 + t^2. \quad (27)$$

The x' and y' variables have been omitted in Eq. (26) because they are trivial. In terms of z and t , the above inequality takes the form

$$\left[\frac{1-\beta}{1+\beta} (z+t)^2 + \frac{1+\beta}{1-\beta} (z-t)^2 \right] < 2. \quad (28)$$

We are therefore dealing with the function localized within an elliptic region defined by this inequality, and can control the t variable in the same manner as we do in the case of the spatial variables appearing in nonrelativistic quantum mechanics. This localization property together with the hyperbolic case is illustrated in Fig. 1.

IV. CONCLUDING REMARKS

We have shown in this paper that the wave functions used in our previous papers are diagonal in the Casimir oper-

ators of the Poincaré group, which specify covariantly the mass and total spin of the hadron. These wave functions are well localized in a space-time region, and undergoes elliptic Lorentz deformation.

An addendum to this paper containing a discussion of Lorentz transformation of the physical wave function and a construction of the representation of the homogeneous Lorentz group is relegated to PAPS.³ It is shown there that solutions of the oscillator equation diagonal in the Casimir operators of the homogeneous Lorentz group are localized within the Lorentz-invariant hyperbolic region illustrated in Fig. 1.

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⁵See AIP document no. PAPS JMAPA-20-1336-12 for twelve pages of discussions of the Lorentz transformation of the physical wave functions, and of the representations of the homogeneous Lorentz group. Order by PAPS number and journal reference from American Institute of Physics, Physics Auxiliary Publication Service, 335 East 45th Street, New York, N.Y. 10017. The price is \$1.50 for each microfiche (98 pages), or \$5 for photocopies of up to 30 pages with \$0.15 for each additional page over 30 pages. Airmail additional. Make checks payable to the American Institute of Physics. This material also appears in *Current Physics Microfilm*, the monthly microfilm edition of the complete set of journals published by AIP, on the frames immediately following this journal article.