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Deuteron Elastic Electromagnetic Form Factor in Relativistic Harmonic Oscillator Model

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Recent *e-d* elastic scattering experiments show that the deuteron elastic electromagnetic form factor behaves like $(Q^2)^{-5}$ at large momentum transfers. This fact suggests that we can observe a possible six-quark configuration besides the ordinary proton-neutron bound state configuration in the deuteron state, because the power 5 is considered to come directly from the degree of freedom of the internal orbital motion in the relativistic harmonic oscillator model, for the same reason as the pion form factor of the simple pole type and the nucleon form factor of the dipole type. Using the theoretical formula of the deuteron form factor given by the model, we analyze the experimental data and then determine the probability of finding the six-quark configuration. Finally, a simple potential model is introduced to connect the probability with possible dibaryon resonance states. Consistent numerical relations are obtained between the deuteron form factor and the dibaryon resonances.

§ 1. Introduction

Recent experiments[1] of high energy electron-deuteron elastic scattering call our attention to an interesting behaviour of the deuteron electromagnetic form factor approaching to $(Q^2)^{-5}$ in the region of large Q^2, Q^2 being the invariant momentum transfer squared. Ordinary nuclear physics, in which the deuteron is a loosely bound system composed of two elementary particles—structureless proton and neutron, never gives such a hard Q^2-dependence for the form factor but only a soft one falling down more rapidly than the experimental result for increasing Q^2 as a reflection of loose binding. The experiments, therefore, seem to us to suggest that the deuteron state has a hadron physics component—for example, a six-quark configuration in addition to the ordinary proton-neutron bound state in nuclear physics. This view would be compatible with the recent discovery of dibaryon states[2] and their possible interpretations based on hadron physics.[3]

The possible existence of the six-quark configuration is also presumed by the well-known experimental facts that the pion and nucleon electromagnetic form factors are well described by the empirical formulas of the simple pole type and of the dipole type, respectively. If the powers '1' and '2' of these form factors come from the degree of freedom of the internal orbital motion in pion and nucleon,[*] then we can suppose that the hard component of the deuteron form factor

[*] This fact was firstly shown by Fujimura, Kobayashi and Namiki (see Ref. 5)). Later, some authors derived the same results through the discussion of the dimensional counting rule on the basis of renomalizable and scale invariant field theory (see Ref. 6)).

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originating from the six-quark configuration should behave like $(Q^2)^{-5}$ at larger Q^2. Within the framework of the relativistic harmonic oscillator model with the definite metric,[4),*)] in fact, one of the present authors and his collaborators gave the theoretical form factors

$$F_\pi(Q^2)=\left[1+\frac{Q^2}{2M_\pi^2}\right]^{-1}\exp\left[-\frac{1}{4\alpha_\pi}\frac{Q^2}{1+(Q^2/2M_\pi^2)}\right], \tag{1·1}$$

$$F_N(Q^2)=\left[1+\frac{Q^2}{2M_N^2}\right]^{-2}\exp\left[-\frac{1}{2\alpha_N}\frac{Q^2}{1+(Q^2/2M_N^2)}\right] \tag{1·2}$$

for pion and nucleon, respectively, and then pointed out that the powers '1' and '2' mean the number of relative coordinates of the constituent quarks in pion and nucleon. For details, see Refs. 5), 7) and the Appendix of this paper. For the sake of exhibition, the theoretical curves of F_π and F_N given by Eqs. (1·1) and (1·2) are shown together with experimental plot in Fig. 1. Note here that we have used the $SU(3)$-symmetric masses, $M_\pi=0.558$ GeV and $M_N=1.097$ GeV, and the approximately common mass formula constants $\alpha_\pi=0.5\,(\mathrm{GeV}/c)^2$ and $\alpha_N=0.44\,(\mathrm{GeV}/c)^2$.

In this paper we analyze the hard component of the deuteron form factor

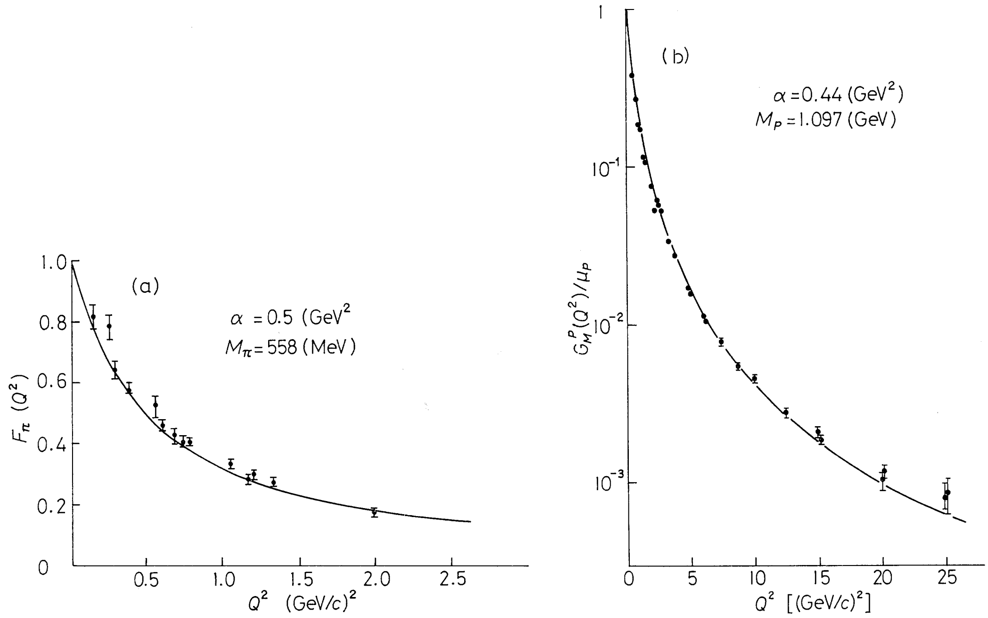

Fig. 1. (a) The electromagnetic pion form factor in the RHOM model and comparison with experiments. (b) The electromagnetic proton form factor in the RHOM model and comparison with experiments.

*) In what follows, we shall use the abbreviation RHOM for this model.

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using the theoretical formula obtained from the six-quark configuration in the RHOM, and give a close relation of the hard component with a possible dibaryon resonance using a simple potential model.

§ 2. Phenomenological analysis of the deuteron form factor based on the RHOM formula

In the preceding section we have emphasized the similarity of the power behaviour of the form factors between the deuteron case and the pion and nucleon cases. Nevertheless, there exists an essential difference between the deuteron state and the pion and nucleon states, because the dominant component of the deuteron wave function is undoubtedly given by ordinary nuclear physics. The six-quark configuration is only its small component. Consequently, it is allowed to assume that the deuteron wave function is written down as

$$\Phi_D = \Phi_{NP} \cos\theta + \Phi_{6q} \sin\theta\,, \tag{2·1}$$

where Φ_{NP} represents a loosely bound state of proton and neutron to be identified with the ordinary deuteron state when the six-quark component Φ_{6q} is discarded. Now we suppose that $|\cos\theta| \gg |\sin\theta|$, and further that Φ_{NP} has nonzero values only outside the 'hard core' region of the ordinary nuclear force, while Φ_{6q} distributes only inside the 'hard core'. Hence the introduction of Φ_{6q} implies that we have assumed the existence of a new attractive force originating from the hadron physics origin inside the 'hard core'. Such an attractive force will be schematized by a simple potential model in § 3.

Now we have the deuteron form factor

$$F_D(Q^2) = F_{NP}(Q^2)\cos^2\theta + F_{6q}(Q^2)\sin^2\theta\,, \tag{2·2}$$

where $F_{NP}(Q^2)$ and $F_{6q}(Q^2)$ are form factors obtained from Φ_{NP} and Φ_{6q}, respectively. It should be remarked that $F_{NP}(Q^2)$ is a rapidly decreasing function of Q^2 for increasing Q^2, because the ordinary deuteron wave function describes a loosely bound system spreading over a rather wide region. So we can observe only $F_{6q}(Q^2)\sin^2\theta$ in the region $Q^2 \gtrsim 1\,(\mathrm{GeV}/c)^2$. This is the base on which we analyze phenomenologically the experimental plot of the deuteron form factor using the theoretical formula for $F_{6q}(Q^2)$. As derived in the Appendix, the RHOM model gives us the theoretical formula

$$F_{6q}(Q^2) = \left[1 + \frac{Q^2}{2M_D^2}\right]^{-5} \exp\left[-\frac{5}{4\alpha_D}\frac{Q^2}{1+(Q^2/2M_D^2)}\right] \tag{2·3}$$

which certainly approaches $(Q^2)^{-5}$ at larger Q^2. It must be noticed here that we have discarded the spin-unitary spin part of the deuteron wave function and its contribution to the Q^2-dependence of the deuteron form factor. Recalling the arguments to obtain the pion and nucleon form factors within the framework of the

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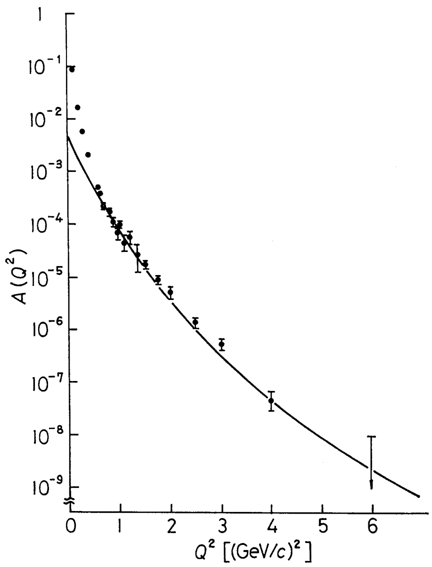

Fig. 2. Fit of $|F_{6q}(Q^2)\sin^2\theta|^2$ with experimental $A(Q^2)$ in the region of larger $Q^2(\gtrsim 1$ (GeV/c)^2).

RHOM together with the $SU(6)_M$ scheme of the spin-unitary spin dependence, we may conclude that the Q^2-dependence coming from the spin-unitary spin part gives only a constant factor of order 1.*) Throughout this paper we shall go on only with the orbital wave function. we will deal with the contribution of the spin-unitary spin part to the Q^2-dependence in a forthcoming chance.

We are now at the position to analyze the experimental result shown in Fig. 2 along the line of thought mentioned above. First we have to fix the value of α_D using the formula $\alpha_{Nq}=(N)^{3/2}\kappa$ derived in the Appendix for an N-quark system. If κ is so determined as to give $\alpha_P \simeq 0.5\,(\mathrm{GeV}/c)^2$ in the proton case, then we have $\alpha_D \simeq 1.4\,(\mathrm{GeV}/c)^2$. It should be remarked that the nonzero region of Φ_{6q} with this value of α_D nearly coincides with the 'hard core' region of the nuclear force. This is one of the satisfactory features of our model. With $\alpha_D \simeq 1.4\,(\mathrm{GeV}/c)^2$, we can proceed to the next procedure of finding the best-fit of the theoretical curve $F_{6q}(Q^2)\sin^2\theta$ with the experimental plot in the region of larger $Q^2(\gtrsim 1$ (GeV/c)^2), by adjusting values of M_D and $\sin^2\theta$. Practically we have performed this procedure, using the plot of $A \equiv F_D{}^2$ obtained by the Rosenbluth formula

$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}}[A(Q^2)+B(Q^2)\tan^2(\theta_e/2)]$$

from observation of electron-deuteron elastic scattering for small scattering angles ($\theta_e \simeq 0$) (see Fig. 2). Thus the procedure gives us $M_D{}^2 \simeq 1.5\,(\mathrm{GeV})^2$ and $\sin^2\theta \simeq 0.07$.**) Therefore, we can conclude that the probability of finding the six-quark configuration in the deuteron state is about 7%. Furthermore if necessary, one could assert that the symmetric mass of a possible deuteron multiplet is nearly equal to $M_D \simeq \sqrt{1.5} \simeq 1.2$ GeV.

*) See Ref. 7), especially see the paper by S. Saito. As for the $SU(6)_M$ symmetry, see also Ref. 8).

**) Similar results were obtained by some authors in Ref. 9) along the line of the same analysis using the empirical pentapole fit to the deuteron form factor.

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§ 3. Possible connection with dibaryon states

In this section we schematize a simple potential model to give the six-quark configuration in the deuteron state, and discuss a possible connection of the probability ($\sin^2\theta$ in § 2) with the elastic width of dibaryon resonance states.

Let us start our discussion with the following internal orbital wave function

$$\Phi(r, s, r', s', R) = \phi_p(r, s)\,\phi_n(r', s')\,\psi(R) \tag{3·1}$$

for a proton-neutron system. Variables (r, s) and (r', s') are, respectively, relative coordinates of constituent quarks in the proton and the neutron. Variable R stands for the relative coordinate between the two centre-of-mass coordinates of the proton and the neutron. Following ordinary nuclear physics, $\psi(R)$ should vanish inside the 'hard core' region of the nuclear force. However, we want to make a model which enables the deuteron state to have the six-quark configuration never vanishing inside the 'hard core'. Defining $\psi_{NP}(R) = \psi(R)\,\theta(R-R_c)$ and $\psi_c(R) = \psi(R)\,\theta(R_c-R)$ in which θ is the Heaviside step function and R_c the 'hard core' radius, then we have

$$\psi(R) = \psi_{NP}(R) + \psi_c(R) \tag{3·2}$$

by which the whole wave function Φ is decomposed as

$$\Phi \equiv \phi_p\phi_n\psi_{NP} + \phi_p\phi_n\psi_c\,. \tag{3·3}$$

Here we equate the first and second terms of Eq. (3·3) to $\Phi_{NP}\cos\theta$ and $\Phi_{6q}\times\sin\theta$ of Eq. (2·1), respectively, and then replace Φ_{6q} with the RHOM wave function given in the Appendix. This is the outline of our schedule. Our task in this section is to discuss $\psi(R)$ by a simple potential model and to find the relation of $\sin^2\theta$ to the elastic width of dibaryon resonance states.

In the relativistic scheme, variable R has four components $(\boldsymbol{R}, R_0)$, but we suppress here the dependence of ψ on relative time R_0. The angle dependence of ψ is determined and can be separated from the $|\boldsymbol{R}|$-dependence if we fix the angular momentum state of the proton-neutron state, for example, to be in S-state. Then we have only to give the dependence of ψ on $|\boldsymbol{R}|$, for which we put here a nonrelativistic Schrödinger equation

$$\frac{d^2u(R)}{dR^2} + M(E - V(R))\,u(R) = 0 \tag{3·4}$$

for $u(R) \equiv R\psi(R)$, where we have rewritten $|\boldsymbol{R}|$ by the same letter R again. Equation (3·4) is designed for a proton-neutron system with reduced mass $(M/2)$, M being the physical nucleon mass.

Now let us suppose that the potential $V(R)$ can be represented schematically by Fig. 3. The ordinary nuclear physics looks upon the very high potential barrier located around R_c as the 'hard core' with infinite height. The attractive

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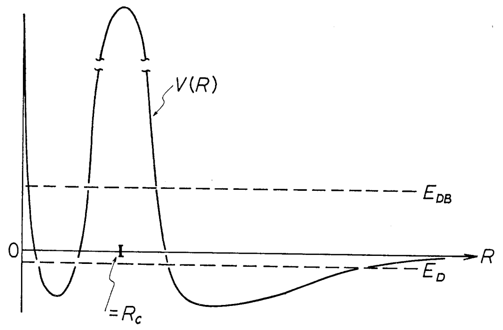

Fig. 3. Schematical representation of the potential $V(R)$.

force inside the barrier is so designed as to get a nonzero $u_c(R) \equiv R\psi_c(R)$ (see Eq. (3·2)) for the origin of the six-quark configuration. It may be obvious that this force also has dibaryon resonance states. Of course, the attractive force never comes from the ordinary nuclear physics but from hadron physics. We shall not enter into detailed discussion on its origin.

Needless to say, the appearance of ψ_c in the deuteron state is a direct result of the tunnel effect passing through the barrier around R_c from the right to the left, namely, to the inside of the 'hard core'. Hence we can put

$$\sin^2\theta \sim P_t \tag{3·5}$$

in the sense of the order of magnitude, where P_t stands for the transmission probability of the tunnel effect. Owing to the very high barrier, it holds that $P_t \ll 1$. On the other hand, the potential as schematized in Fig. 3 must have a metastable state to be observed as a dibaryon resonance. Such a metastable state will decay into proton and neutron due to the tunnel effect passing through the barrier from the left to the right. The reciprocity principle gives us the same transmission probability for it as the above P_t. Consequently, the elastic width of the dibaryon resonance is given by

$$\Gamma_{DB}^{\mathrm{el}} \sim \tau^{-1} P_t\,, \tag{3·6}$$

where $\tau \sim (R_c M/k_c)$ is the average travelling time of the attractive force region inside the barrier, k_c being the average momentum there. Rigorously speaking, the transmission probability for the dibaryon level is different from that for the deuteron level, because it depends on energy. However, we can neglect the difference between them because of the very high barrier. That is to say, it holds that $P_t(E_{DB}) \simeq P_t(E_D)$ if the average height of the barrier is much larger than E_{DB} and $|E_D|$. Now we must impose the condition

$$k_c R_c \sim \pi \tag{3·7}$$

on the average momentum k_c, to keep the metastable state—the dibaryon state. Thus the elastic width is given by

$$\Gamma_{DB}^{\mathrm{el}} \sim \frac{\pi P_t}{(R_c M)^2} M\,. \tag{3·8}$$

Using $P_t \sim \sin^2\theta \simeq 0.07$ for the transmission probability (see the preceding section)

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and $R_c \simeq 2.5M^{-1}$ for the 'hard core' radius, we have

$$\Gamma^{\text{el}}_{DB} \sim 33\ \text{MeV}\ .$$

This may be compared with the observed value $(\Gamma^{\text{el}}_{DB})_{\text{exp}} \simeq 30$ MeV obtained by the recent experiment of the $^3F_3$ dibaryon resonance[10),*] (mass $\simeq 2.22$ GeV, total width $\simeq 150$ MeV and elasticity $\simeq 0.2$), although it is discovered by the proton-proton elastic scattering. It seems to us that the agreement is very good in the sense of the order of magnitude.

Finally, we want to sketch the attractive force potential inside the barrier, using (3·7) and $k_c = \sqrt{M(E_{DB} - \overline{V})}$ in which $\overline{V}$ is the average potential depth. By the experimental data of the $^3F_3$ resonance, we have $E_{DB} = M_{DB} - 2M \simeq 0.34M$ and then

$$-\frac{\overline{V}}{M} \sim 1.1\ .$$

The attractive force potential would have the depth $\sim 1.1M$ and the range $\sim 2.5M^{-1}$ in the sense of the order of magnitude.

§ 4. Conclusion

In this paper we have analyzed the hard component of the experimental deuteron electromagnetic form factor using the theoretical formula of the RHOM model, and obtained the probability of finding the six-quark configuration in the deuteron state. One of the important features of the observed deuteron form factor is in its asymptotic bahaviour proportional to $(Q^2)^{-5}$, which is considered in this paper to be a possible appearance of the six-quark configuration in the deuteron state on the analogy of the pion and nucleon cases. If this view is true, then we could also anticipate to observe the asymptotic Q^2-dependences of $(Q^2)^{-8}$ in the triton form factor and of $(Q^2)^{-11}$ in the form factor of an α particle and of $(Q^2)^{-3A+1}$ in a nucleus with mass number A, in general, with a possible saturation effect takes place.

Furthermore, we have attempted to connect the six-quark configuration with the dibaryon resonances recently discovered, in view of a simple potential model.

The remaining works are (i) to give corrections of the deuteron form factor coming from the spin-unitary spin wave function and (ii) to give quantitative discussion on the relation between the deuteron form factor and the dibaryon resonances. They will be reported in the near future.

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*) Besides the $^3F_3$ resonance, we have a few indications of dibaryon resonances with mass and elastic width of the same order of magnitude.

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Appendix

——*Form Factor of an N-quark System in the RHOM Model*——

We assume that the internal orbital wave function obeys the following equation with a relativistic harmonic oscillator potential:

$$[\sum_{i=1}^{N} p^{(i)2} + \kappa^2 \sum_{i>j=1}^{N} (x^{(i)} - x^{(j)})^2] \Phi_{Nq}(x^{(1)}, \cdots, x^{(N)}) = 0\,, \qquad (\mathrm{A}\cdot 1)$$

where $x^{(i)}$ stands for the coordinate of the i-th quark and $p^{(i)} = (i\partial/\partial x^{(i)})$, and κ^2 is a constant. The potential term is rewritten in the form

$$\sum_{i>j=1}^{N} (x^{(i)} - x^{(j)})^2 = (x^{(1)}, \cdots, x^{(N)}) \begin{pmatrix} n & -1 & \cdots & \cdots & -1 \\ -1 & n & -1 & \cdots & -1 \\ \vdots & -1 & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & -1 \\ -1 & -1 & \cdots & -1 & n \end{pmatrix} \begin{pmatrix} x^{(1)} \\ \vdots \\ x^{(N)} \end{pmatrix}, \qquad (\mathrm{A}\cdot 2)$$

where $n = N-1$. Eigenvalues of the matrix are given by the equation

$$\begin{vmatrix} n-\lambda & -1 & \cdots & \cdots & -1 \\ -1 & n-\lambda & -1 & \cdots & -1 \\ \vdots & -1 & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & -1 \\ -1 & -1 & \cdots & -1 & n-\lambda \end{vmatrix} = (-1)^N (\lambda - N)^n \lambda = 0\,, \qquad (\mathrm{A}\cdot 3)$$

whose eigenvalues are $\lambda = 0$ and $\lambda = N$. The first eigenvector belonging to $\lambda = 0$ is a column vector $\boldsymbol{v}$ whose all components are equal to $N^{-1/2}$, but the other eigenvectors are arbitrary unit vectors $\boldsymbol{u}^{(i)}$ $(i = 1, \cdots, n)$ orthogonal to the first and to each other because the eigenvalue $\lambda = N$ is n-fold degenerate. Consequently, we can diagonalize the quadratic form (A·2) by the matrix $U = (\boldsymbol{v}, \boldsymbol{u}^{(1)}, \cdots, \boldsymbol{u}^{(n)})$, namely,

$$\sum_{i>j=1}^{N} (x^{(i)} - x^{(j)})^2 = N \sum_{i=1}^{n} r^{(i)2}\,, \qquad (\mathrm{A}\cdot 4)$$

where the relative coordinates $r^{(i)}$'s are given by

$$\begin{pmatrix} x^{(1)} \\ \vdots \\ x^{(N)} \end{pmatrix} = U \begin{pmatrix} x^{(0)} \\ r^{(1)} \\ \vdots \\ r^{(n)} \end{pmatrix} \qquad (\mathrm{A}\cdot 5)$$

in which

$$x^{(0)} = \frac{1}{\sqrt{N}} (x^{(1)} + \cdots + x^{(N)})\,. \qquad (\mathrm{A}\cdot 6)$$

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Denoting momenta conjugate to new variables $x^{(0)}$ and $r^{(i)}$ by $p^{(0)}$ and $p_r^{(i)}$ ($i=1, \cdots, n$), then we get

$$\begin{pmatrix} p^{(0)} \\ p_r^{(1)} \\ \vdots \\ p_r^{(n)} \end{pmatrix} = U^T \begin{pmatrix} p^{(1)} \\ \vdots \\ \vdots \\ p^{(N)} \end{pmatrix}. \tag{A·7}$$

Hence Eq. (A·1) becomes

$$[p^{(0)2} + \sum_{i=1}^{n} (p_r^{(i)2} + N\kappa^2 r^{(i)2})]\Phi(x^{(0)}, r^{(1)}, \cdots, r^{(n)}) = 0 .$$

Using the total momentum

$$P = \sqrt{N} p^{(0)} \tag{A·8}$$

and the operators

$$a_{r\mu}^{(i)} = \frac{1}{\sqrt{2\alpha_N}} \left(\sqrt{N} p_{r\mu}^{(i)} - i \frac{\alpha_N}{\sqrt{N}} r_\mu^{(i)} \right) : \alpha_N = N^{3/2}\kappa , \tag{A·9}$$

then we have the equation

$$\left. \begin{aligned} &[P^2 - M_{0p}^2]\Phi_{Nq} = 0 , \\ &M_{0p}^2 = -2\alpha_N \sum_{i=1}^{n} a_{r\mu}^{(i)\dagger} a_r^{(i)\mu} + \text{const.} \end{aligned} \right\} \tag{A·10}$$

If we impose on Φ_{Nq} the subsidiary condition formulated by Takabayasi, we can easily obtain the following solution:

$$\Phi_{Nq}(r^{(1)}, \cdots; P) = \left(\frac{\alpha_N}{\pi N} \right)^n \exp\left[\frac{\alpha_N}{2N} \left(g^{\mu\nu} - 2\frac{P^\mu P^\nu}{M^2} \right) \left(\sum_{i=1}^{n} r_\mu^{(i)} r_\nu^{(i)} \right) \right], \tag{A·11}$$

where we have dropped out the plane wave part for the centre-of-mass coordinate. It is well known that the wave function (A·11) is characterized by the Lorentz contraction effect.

Now we can give the form factor of an N-quark system by

$$F_{Nq}(q^2) = \int \Phi_{Nq}^*(r^{(1)}, \cdots; P_F) \exp[-iq \cdot \sum_{i=1}^{n} u_1^{(i)} r^{(i)}] \Phi_{Nq}(r^{(1)}, \cdots; P_I) \times d^4 r^{(1)} \cdots d^4 r^{(n)} , \tag{A·12}$$

where $n_1^{(i)}$ is the first component of vector $\boldsymbol{u}^{(i)}$ subject to the normalization condition

$$\sum_{i=1}^{n} |u_1^{(i)}|^2 = \frac{n}{N} . \tag{A·13}$$

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After elementary calculation using operators defined by Eq. (A·9) and also using (A·13), we can easily find the following formula:

$$F_{Nq}(Q^2)=\frac{1}{[1+(Q^2/2M_{Nq}^2)]^n}\exp\left[-\frac{n}{4\alpha_N}\frac{Q^2}{1+(Q^2/2M_{Nq}^2)}\right] \tag{A·14}$$

with $Q^2=-q^2$.

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