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VECTOR DOMINANCE MODEL AND GARI-KRÜMPELMANN FORMULA FOR
THE NUCLEON ELECTROMAGNETIC FORM FACTOR

3W3450

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Abstract

Electromagnetic form factors of nucleon are investigated by using the vector dominance model (VDM) and the formulae that are proposed by Gari and Krümpelmann (GK) to synthesize VDM and the perturbative QCD. We simplify and generalize the formulae given by GK. The existing data of nucleon electromagnetic form factors are realized remarkably well. Although the incorporation of QCD term improves the fit, the present experimental data on the form factors are not accurate enough to exclude simple naive vector dominance model.

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Recently, experimental data for the electromagnetic form factors have become accurate from the low to high squared momentum transfer $t = Q^2$ [1-12]. For high t , the magnetic form factors of nucleons and charge form factor of proton decrease more rapidly than the prediction of the dipole formula, $G_D = (1 + t/0.71)^{-2}$, where t is given in terms of GeV^2 . The neutron electric form factor is very small up to $t = 4 \text{ GeV}^2$. For small t we may explain the experimental data in terms of hadron dynamics, for instance, with recourse to the vector dominance model (VDM) or the dispersive theoretical calculations for the pion and nucleon system. In the vector dominance model (VDM) it is necessary to take the ρ meson mass smaller than the experimental one by 20 %. The following two possibilities were considered on the small ρ meson mass: One is the explanation based on hadron dynamics; the uncorrelated two pion contribution works in reducing the effective mass of the ρ meson [13], and the other is the incorporation of an additional photon- ρ meson form factor that effectively makes the ρ meson mass smaller [14]. For large t we have the prediction of perturbative QCD (PQCD), according to which the charge and magnetic moment form factors F_1 and F_2 are given asymptotically as $F_1 \sim t^{-2} \ln(t/Q_0^2)^{-\gamma}$ and $F_2 \sim t^{-3} \ln(t/Q_0^2)^{-\gamma'}$ where Q_0 , γ and γ' are constants. The experimental results for large t seem to agree with the prediction of PQCD.

Considering that the experimental data have become very accurate and that in the near future ep collider experiments will provide data for very high t , it is a problem of importance to derive formulae that explain the form factors for the low and high t regions systematically. Furuichi and one of the authors assumed the superconvergent dispersion relations [15,16] for F_i ($i = 1,2$) to synthesize the low and high t regions of form factors. They are able to explain the experimental data very well including the recent SLAC data [9-12]. Gari and Krümpelmann (GK) [17] proposed simple formulae, which show VDM for low t region with the ρ and ω meson poles and for high t region PQCD behavior. Their formulae reproduce the magnetic form factor of proton very well but for the other form factors the agreement with experiments was not good.

It is the purpose of this paper to investigate the nucleon electromagnetic form factor based on simple phenomenological formulae. First, we examine VDM to see to what extent the simple vector dominance model reproduces the experimental data throughout the low and high t regions. Second, we investigate the effect of PQCD by using the improved formulae of Gari and Krümpelmann with simplification of the QCD term and incorporation of the vector bosons appearing in the Review of Particle Properties [18].

In the vector dominance model the charge and magnetic moment form factors of nucleons, F_1^I and F_2^I (I being the isospin), are given as

$$F_i^I(t) = P_i^I(t) \quad (I = 0, 1; i = 1, 2). \quad (1)$$

Here $P_i^I(t)$ are

$$P_i^I(t) = c_i^I - t \sum_{k=1}^{N_I} \frac{a_i(M_k^I)}{t + (M_k^I)^2}, \quad (2)$$

M_k^I 's denote the mass of vector bosons with the isospin I , $a_i(M_k^I)$ are constants and the normalizations of P_i^I at $t = 0$ are taken as $c_1^I = 1$ and $c_2^I = 2\kappa_I$, where κ_I is the anomalous magnetic moment with the iso-spin I ; $\kappa_0 = (\kappa_p + \kappa_n)/2$ and $\kappa_1 = (\kappa_p - \kappa_n)/2$ with κ_p and κ_n being the anomalous magnetic moments of proton and neutron respectively.

The following two constraints are considered on the asymptotic behavior of P_i^I for $t \rightarrow \infty$:

- (a) $P_1^I \rightarrow 0$ and $tP_2^I \rightarrow 0$,
- (b) $tP_1^I \rightarrow 0$ and $t^2P_2^I \rightarrow 0$.

The constraint (a) leads to

$$\sum_{i=1}^{N_I} a_1(M_i^I) = 1, \quad \sum_{i=1}^{N_I} a_2(M_i^I) = 2\kappa_I, \quad \sum_{i=1}^{N_I} (M_i^I)^2 a_2(M_i^I) = 0.$$

To effect the constraint (b) the following additional conditions are required:

$$\sum_{i=1}^{N_I} (M_i^I)^2 a_1(M_i^I) = 0, \quad \sum_{i=1}^{N_I} (M_i^I)^4 a_2(M_i^I) = 0.$$

When the condition (a) is imposed, P_i^I are given in terms of the independent parameters $\bar{A}_1(M_i^I)$ ($i = 1, \dots, N_I - 1$) and $\bar{A}_2(M_i^I)$ ($i = 1, \dots, N_I - 2$). We have

$$P_1^{I(a)}(t) = \left[1 - t \sum_{i=1}^{N_I-1} \frac{\bar{A}_1(M_i^I)}{t + (M_i^I)^2} \right] \frac{(M_{N_I}^I)^2}{t + (M_{N_I}^I)^2}, \quad (3)$$

$$P_2^{I(a)}(t) = [2\kappa_I - t \sum_{i=1}^{N_I-2} \frac{\bar{A}_2(M_i^I)}{t + (M_i^I)^2}] \frac{(M_{N_I-1}^I)^2 (M_{N_I}^I)^2}{[t + (M_{N_I-1}^I)^2][t + (M_{N_I}^I)^2]}. \quad (4)$$

For the case (b) P_i^I are expressed as

$$P_1^{I(b)}(t) = [1 - t \sum_{i=1}^{N_I-2} \frac{\bar{A}_1(M_i^I)}{t + (M_i^I)^2}] \frac{(M_{N_I-1}^I)^2 (M_{N_I}^I)^2}{[t + (M_{N_I-1}^I)^2][t + (M_{N_I}^I)^2]}, \quad (5)$$

$$P_2^{I(b)}(t) = [2\kappa_I - t \sum_{i=1}^{N_I-3} \frac{\bar{A}_2(M_i^I)}{t + (M_i^I)^2}] \frac{(M_{N_I-2}^I)^2 (M_{N_I-1}^I)^2 (M_{N_I}^I)^2}{[t + (M_{N_I-2}^I)^2][t + (M_{N_I-1}^I)^2][t + (M_{N_I}^I)^2]}. \quad (6)$$

The residues at the vector boson poles in P_j^I , $a_j(M_i^I)$ ($j = 1, 2$; $i = 1, \dots, N_I$), are given in terms of $\bar{A}_j$ as follows: For the case (a) we have

$$\begin{aligned} a_1(M_i^I) &= \frac{(M_{N_I}^I)^2 \bar{A}_1(M_i^I)}{(M_{N_I}^I)^2 - (M_i^I)^2} \quad (i = 1, \dots, N_I - 1), \\ a_1(M_{N_I}^I) &= 1 - \sum_{i=1}^{N_I-1} \frac{(M_{N_I}^I)^2}{(M_{N_I}^I)^2 - (M_i^I)^2} \bar{A}_1(M_i^I), \\ a_2(M_i^I) &= \frac{(M_{N_I}^I)^2 (M_{N_I-1}^I)^2 \bar{A}_2(M_i^I)}{[(M_{N_I}^I)^2 - (M_i^I)^2][(M_{N_I-1}^I)^2 - (M_i^I)^2]} \quad (i = 1, \dots, N_I - 2), \\ a_2(M_{N_I-1}^I) &= -2\kappa_I \frac{(M_{N_I}^I)^2}{(M_{N_I}^I)^2 - (M_{N_I-1}^I)^2} \\ &\quad + \sum_{i=1}^{N_I-1} \frac{(M_{N_I}^I)^2 (M_{N_I-1}^I)^2 \bar{A}_2(M_i^I)}{[(M_{N_I}^I)^2 - (M_{N_I-1}^I)^2][(M_i^I)^2 - (M_{N_I-1}^I)^2]}, \\ a_2(M_{N_I}^I) &= 2\kappa_I \frac{(M_{N_I-1}^I)^2}{(M_{N_I}^I)^2 - (M_{N_I-1}^I)^2} \\ &\quad + \sum_{i=1}^{N_I-1} \frac{(M_{N_I}^I)^2 (M_{N_I-1}^I)^2 \bar{A}_2(M_i^I)}{[(M_i^I)^2 - (M_{N_I}^I)^2][(M_{N_I-1}^I)^2 - (M_{N_I}^I)^2]}, \end{aligned} \quad (7)$$

and for the case (b) similar expressions may be obtained.

For the vector dominance model we examine the cases with conditions (a) and (b); the charge and magnetic moment form factors are given by (1), namely, $F_i^I = P_i^{I(a)}$ or $F_i^I = P_i^{I(b)}$.

Let us now give the formulae which satisfy the prediction of PQCD for a large t . We simplify the QCD factor in the Gari Krümpelmann formulae and generalize the pole terms by taking account of vector bosons that are reported in Ref.[18]. The form factors are

$$F_i^I(t) = P_i^{I(a)}(t) F^{QCD}(t), \quad (8)$$

It is the purpose of this paper to investigate the nucleon electromagnetic form factor based on simple phenomenological formulae. First, we examine VDM to see to what extent the simple vector dominance model reproduces the experimental data throughout the low and high t regions. Second, we investigate the effect of PQCD by using the improved formulae of Gari and Krümpelmann with simplification of the QCD term and incorporation of the vector bosons appearing in the Review of Particle Properties [18].

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$$\sum_{i=1}^{N_I} (M_i^I)^2 a_1(M_i^I) = 0, \quad \sum_{i=1}^{N_I} (M_i^I)^4 a_2(M_i^I) = 0.$$

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$$P_2^{I(a)}(t) = [2\kappa_I - t \sum_{i=1}^{N_I-2} \frac{\bar{A}_2(M_i^I)}{t + (M_i^I)^2}] \frac{(M_{N_I-1}^I)^2 (M_{N_I}^I)^2}{[t + (M_{N_I-1}^I)^2][t + (M_{N_I}^I)^2]}. \quad (4)$$

For the case (b) P_i^I are expressed as

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$$P_2^{I(b)}(t) = [2\kappa_I - t \sum_{i=1}^{N_I-3} \frac{\bar{A}_2(M_i^I)}{t + (M_i^I)^2}] \frac{(M_{N_I-2}^I)^2 (M_{N_I-1}^I)^2 (M_{N_I}^I)^2}{[t + (M_{N_I-2}^I)^2][t + (M_{N_I-1}^I)^2][t + (M_{N_I}^I)^2]}. \quad (6)$$

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Let us now give the formulae which satisfy the prediction of PQCD for a large t . We simplify the QCD factor in the Gari Krümpelmann formulae and generalize the pole terms by taking account of vector bosons that are reported in Ref.[18]. The form factors are

$$F_i^I(t) = P_i^{I(a)}(t) F^{QCD}(t), \quad (8)$$

large. It must be noticed that in WT we are able to reproduce the experimental data quite well by keeping the ρ meson mass at the experimental value as is shown in Table I(b). In this case the factor F^{QCD} in (8) works as an additional incorporation of the photon- ρ meson form factor as in Ref.[14]. Although the assumption of PQCD behavior for the form factors greatly improves the results, information at higher momentum transfer are required to draw conclusion that the contribution from vector boson poles vanishes asymptotically so that the effect of PQCD actually dominates in the large t region for the nucleon electromagnetic form factor. In this paper we have simplified the QCD factor as is given by (9) to reduce the number of parameters, however, we may perform similar calculations by using the same function for F_{QCD} that was proposed by Gari and Krümpelmann. By taking account of observed vector bosons in the original GK formula, the experimental data are parametrized very well throughout the low and high t regions; we have $\chi^2_{min}/DOF \sim 1.0$. When the experimental data of form factors in the region t above 100 GeV² become available, it will be necessary to elaborate the QCD factor by considering higher order effects etc.

The factorized formula of VDM and F^{QCD} given by (8) is analogous to the form factor version of the Veneziano amplitude, given by Di Vecchia and Drago [19], that represents the dual nature of Regge pole and vector bosons. The formula is an interpolation of VDM and PQCD, and it implies existence of duality in the vector boson resonances and the quark-gluon system.

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Table captions

Table I. Chi square values vs. the number of vector bosons N_V and N_S and the ρ meson mass m_ρ for VDM and WT.

Table I(a). Vector dominance model.

Table I(b). The improved GK; WT. Λ is the parameter appearing in (9).

Table II. $\bar{A}_j(M_i^I)$ appearing in (5) and (6).

Table II (a). $\bar{A}_1(M_i^I)$ and $\bar{A}_2(M_i^I)$ for VDM.

Table II (b). $\bar{A}_1(M_i^I)$ and $\bar{A}_2(M_i^I)$ for WT.

Table III. The residues at the poles of $P^{(a)}$ or $P^{(b)}$.

Table III(a). Vector dominance model; VDM(a) and VDM(b).

Table III(b). The improved GK; WT1, WT2 and WT3.

Figure captions

Fig.1. $G_M^p/(\mu^p G_D)$. The solid curve is the calculation by WT2 with $N_V = 4$, $N_S = 5$, $m_\rho = 0.63$ GeV and $\Lambda = 0.8$ GeV, the dashed one GK [18] and the dash-dotted one VDM (b) with $N_V = 4$, $N_S = 5$ and $m_\rho = 0.64$ GeV.

○: Borkowski et al.[7]. ●: Price et al.[2]. ▽: Ch.Berger et al.[3].
 △: Bosted et al.[10]. □: Bartel et al.[4]. ■: Sill et al.[12].

Fig.2. G_E^p/G_D . The dashed curve is the calculation by GK model 3 [19]. See the caption of Fig.1.

Fig.3. $G_M^n/(\mu^n G_D)$. The dashed curve is the calculation by GK [18].

△: Rock et al.[8]., △: Lung et al.[11]. □: Bartel et al.[4].
 ○: Noncoincidence data cited in Bartel et al.[4].
 ◇: Combined analysis; Stein et al.[1] and Bartel et al.[4].

Fig.4. $(G_E^n/G_D)^2$. The dashed curve is the calculation by GK model 3 [19].

○: Bartel et al.[4]. ●: Hanson et al.[5]. △: Lung et al.[11].

M_i^I (GeV)	VDM (a)		VDM (b)	
	$m_\rho = 0.64$ GeV $a_1(M_i^I)$	$a_2(M_i^I)$	$m_\rho = 0.64$ GeV $a_1(M_i^I)$	$a_2(M_i^I)$
$\rho(m_\rho)$	0.931	5.205	0.514	5.586
$\rho'(1.465)$	-0.106	-1.496	3.820	-4.855
$\rho''(1.700)$	0.641	-0.700	-4.120	3.274
$\rho'''(2.110)$	-0.466	0.697	0.786	-0.298
$\omega(0.783)$	4.913	0.348	5.862	-1.132
$\omega'(1.394)$	29.837	-5.164	17.759	-1.383
$\omega''(1.594)$	-56.371	14.043	-26.517	0.905
$\phi(1.020)$	-10.363	-0.292	-10.256	1.752
$\phi'(1.680)$	32.983	-9.054	14.151	-0.263

Table III (a)

M_i^I (GeV)	WT1		WT2		WT3	
	$m_\rho = 0.6$ GeV $a_1(M_i^I)$	$a_2(M_i^I)$	$m_\rho = 0.63$ GeV $a_1(M_i^I)$	$a_2(M_i^I)$	$m_\rho = 0.7681$ GeV $a_1(M_i^I)$	$a_2(M_i^I)$
$\rho(m_\rho)$	0.747	3.090	1.904	2.142	2.325	5.204
$\rho'(1.465)$	-4.192	-7.904	-25.235	-19.434	-21.525	-16.079
$\rho''(1.700)$	2.445	14.136	25.688	33.688	25.268	21.432
$\rho'''(2.110)$	2.000	-5.615	-1.357	-12.690	-5.069	-6.850
$\omega(0.783)$	1.802	0.048	3.975	11.619	7.680	10.482
$\omega'(1.394)$	-5.726	-0.666	133.640	81.683	152.592	92.625
$\omega''(1.594)$	4.924	0.498	-330.013	-124.764	-344.154	-155.248
$\phi(1.020)$			-21.382	-35.181	-31.497	-34.353
$\phi'(1.680)$			214.780	66.523	216.380	86.374

Table III (b)

M_i^I (GeV)	VDM (a)		VDM (b)	
	$m_\rho = 0.64$ GeV		$m_\rho = 0.64$ GeV	
	$a_1(M_i^I)$	$a_2(M_i^I)$	$a_1(M_i^I)$	$a_2(M_i^I)$
$\rho(m_\rho)$	0.931	5.205	0.514	5.586
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Table III (a)

M_i^I (GeV)	WT1		WT2		WT3	
	$m_\rho = 0.6$ GeV		$m_\rho = 0.63$ GeV		$m_\rho = 0.7681$ GeV	
	$a_1(M_i^I)$	$a_2(M_i^I)$	$a_1(M_i^I)$	$a_2(M_i^I)$	$a_1(M_i^I)$	$a_2(M_i^I)$
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Table III (b)

Fig.1

Fig. 2

Fig.3

Fig.4