QUARK MODELS AND ELECTROWEAK EFFECTS

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1. Introduction

Quark models are very useful tool for calculating various effects associated with electroweak interactions [1 - 20]. This paper will deal with the calculation of the current matrix elements (i.e. form factors in the static limit) and with the baryon-baryon-vector meson coupling. The paper by D. Horvat (See p. of this proceedings) deals with hyperon nonleptonic decays.

The baryon axial vector coupling constant g_A and the magnatic moment μ can be calculated by using models in which quarks move inside a confinement without experiencing any mutual correlation [1 - 6; 16 - 20] or by using models with two body forces acting among quarks [8 - 14].

2. Harmonic Oscillator Quark Model

Among the second group of the models it is useful to select those in which the interaction among quarks is of the harmonic oscillator (HO) form [8,9,11,12,13] as they allow explicit separation of the center-of-mass coordinates of a hadron so that the recoil effects can be studied. The models from the first group contain a particular variety of the chiral bag model in which there are two radii. The quark HO models under discussion are quantized composite systems. All physical quantities, i.e. operators, of the composite system, can be expressed in terms of the constituent particle variables $(\vec{r}_i, \vec{p}_i, \vec{s}_i)$.

A simple, but nevertheless quite successful nonrelativistic quark model [12] was successfully extended by including some momentum dependent effects [13]. Quarks were described by free particle, on-mass-shell, Dirac spinors $U(p_i)$, whose momantum dependence was weighted by a Gaussian $G(k_1,k_2,k_3)$. In such a model the wave function in the impulse space has a general form

$$\Psi = f(\vec{P})\, G(\vec{k}_1,\vec{k}_2,\vec{k}_3)\, U(p_1)\, U(p_2)\, U(p_3) \tag{2.1}$$

Here $f(\vec{P})$ is a plane wave which describes motion of the composite object as a whole. The momentum $\vec{p}_i$ in the Dirac spinor is connected to $\vec{k}_i$ by (2.2). This formula implies a completely nonrelativistic dynamics. Yet one has to retain all orders in k/m in spinors to obtain g_A which agrees with the measured value [13].

Each of the existing ingredients in such a "hybrid" model seems justified on an intuitive physical basis. However, the inconsistencies could arise if nonrelativistic variables were used to describe the relativistic interactions of a composite system. The quarks have relativistic internal motion. From some point of view, they behave as almost free particles inside the confinement region. For weakly bound systems an exact expression has been found [21,22], valid in any Lorentz frame, relating the internal variable $\vec{k}_i$ with the momentum $\vec{p}_i$

$$\vec{k}_i = \vec{p}_i + \frac{1}{M(E+M)}\left[\vec{P}\cdot\vec{p}_i + (E+M)E_i\right]\vec{P} \tag{2.2}$$

Here H,E and $\vec{P}$ refer to the composite system. Here

$$\begin{aligned} \mathcal{E}_i^2 &= k_i^2 + m_i^2 \\ E_i^2 &= p_i^2 + m_i^2 \\ E^2 &= \vec{P} + M^2 \\ M &= \sum_i \mathcal{E}_i \end{aligned} \tag{2.3}$$

The composite mass M can either be made equal to the real experimental mass, i.e. mass of the proton, or it can be determined as an expectation value of the sum of the internal energies [15]

$$M_p = \int d^3\rho_s\, d^3\rho_\lambda\, G^2(\rho_s,\rho_\lambda)\left(\sum_\ell \mathcal{E}_\ell\right) \tag{2.4}$$

A general form of the current matrix element corresponding to the momentum transfer $\vec{q}$ and an operator Γ is

$$\begin{aligned}\langle J(\vec{q},\Gamma)\rangle = &\int d^3\rho_s\, d^3\rho_\lambda\, d^3\rho_s'\, d^3\rho_\lambda'\, \delta(\vec{\rho}_s - \vec{\rho}_s{}') \cdot \\ &\cdot \delta(\vec{\rho}_\lambda - \vec{\rho}_\lambda{}' - \tfrac{2}{\sqrt{6}}\vec{q})\, Z_1(\rho_1',\rho_1)\, Z_2(\rho_2',\rho_2) \cdot \\ &\cdot G(\rho_s',\rho_\lambda')\, G(\rho_s,\rho_\lambda)\, \bar{U}(\rho_3')\, \Gamma\, U(\rho_3)\end{aligned} \tag{2.5}$$

$$Z_i(\rho_i',\rho_i) = \bar{U}(\rho_i')\,U(\rho_i)\ ; \quad \vec{q} = \vec{P}' - \vec{P}$$

The normalization is fixed by the charge conservation requirement

$$\langle J(\vec{q},\gamma_0)\rangle \xrightarrow[\vec{q}\to 0]{} 1 \tag{2.6}$$

Models allow for two possible couplings to the electroweak fields. Either

$$\gamma^\mu A_\mu \quad ; \quad \gamma^\mu \gamma_5 W_\mu \tag{2.7}$$

or

$$\frac{1}{2m}(\not{p}'\gamma^\mu + \gamma^\mu \not{p})A_\mu \ ; \ \frac{1}{2m}(\not{p}'\gamma^\mu\gamma_5 + \gamma^\mu\gamma_5\not{p})W_\mu \tag{2.8}$$

The last choice, used in ref.[8] will be denoted in tables by FEY. The following Table I and II show some interesting results obtained by using formula (2.4) for the mass M. Some other possibilities are discussed in much greater detail in ref. [15].

Table I (Masses in GeV)				Table II (Masses in GeV)	
α	.262	.271	α	.298	.289
m	.170	.1765	m	.199	.1872
μ	2.777	2.682	μ_{FEY}	2.800	2.368
g_A	1.249	1.250	g_A	1.248	1.248
M	.9046	.9368	M	1.028	.9968

With free-particle on-mass-shell spinors used for quark description, the difference between relativistic[9,11]and non-relativistic HO quark models is not of any practical consequence in the small $\vec{q}$ (momentum transfer) limit, in which one calculates μ and g_A. The model explored here is actually relativised "nonrelativistic" HO model as it uses nonrelativistic gaussian dependent on α as a weighting function in the integral involving relativistic four-component Dirac spinors U (p). The static quantities μ and g_A depend very much on the particular choice of spinors. As the HO model corresponds to either KG equation or its nonrelativistic approximation, the spinorial character of the quarks has to be added into the theory. In the nonrelativistic HO to each quark one simply assignes a two component Pauli spinor χ . The Pauli spinors can be boosted into Dirac spinors so that they aquire "small" components. Ref. [8] chose to boost to the speed of the center-of-mass, so the Dirac spinors depend on P alone. In ref. [13] and here spinors are boosted to a general reference frame. They depend on $\vec{p}_i$s defined by (2.2), so that the small components do influence value of the integral (2.5) and one finds modified values (see Tables I and II) for μ and g_A.

If one neglects dependence of spinors U on the internal variables $\vec{k}_i$, i.e. by substituting

$$\vec{p}_i \rightarrow \frac{1}{3}\vec{P} \qquad (2.7)$$

all products of the spinors can be shifted in front of the integral (2.5) and one obtains nonrelativistic static values μ_p = e/2m, μ_n = - e/3m and g_A = 5/3 for the formfactors. (One needs m = M_p/3 for a rough agreement with experimental values.) This results from the SU(6) spin-flavor symmetry of the baryon (hadron) states which is the same as in the nonrelativistic quark model [1] .

The alternative couplings to photon field and to intermediate-vector-boson field which were used by ref.[8]do not change above conclusions. The model of ref.[8] is actually more complicated, other details have been discussed in ref.[15].

There is a variety of other relativistic models, for example refs.[10,14]. Their conventions and approaches are more or less similar to refs.[8] and[9] so it would be tedious to go into all particular details and choices.

For the sake of completeness let us mention that concerning the spin part two types of extension have been proposed [14]: The Bargmann-Wigner (BW) scheme uses a Dirac spinor and was also known as $\tilde{U}$(12) scheme. The Pauli spin scheme uses a suitably boosted Pauli spinor. The first case was used by ref.[9]while the conventions of ref.[8]correspond to the second choice. In any or these approaches, spinors do not depend on the internal momenta, which always gives $g_A = 5/3$. In the model outlined in this paper the theoretical value for μ and g_A depend only weakly on the particular detailes of a HO model. They are mostly influenced by the general characteristics of the quark models:

- Quarks are spinors and their internal motion is relativistic
- Quarks are confin. d
- Baryon state vect r, appropriate for the description of the static ($\vec{q} \to 0$) properties is predominantly made of valence quarks. It belongs t 56 representation of SU(6) spin-flavor group.

It is hardly surprising that these investigations support the quark structure of baryons and that they are qualitatively and even quantitatively (within 10-15 %) in good agreement with bag-model predictions [1-3,13] , to which we turn next.

3. Chiral Bag Model with "Skin"

It is useful to study axial-vector coupling constants g_A measured in the hyperon semileptonic decays[23-25] together with the axial-vector isoscalar coupling constant g_A^S which can be estimated from the Bjorken sum rules[26-28] for the deep-inelastic scattering of polarized electrons on a polarized proton.

The estimated value of g_A^S stresses the relativistic character of the internal quark motion, which has to be present in any successful quark model. In the static quark model SU(6) spin-flavor symmetry of the nucleon wave function predicts 5/3 for the isovector g_A^I responsible for $n - p +$ leptons decay. The same considerations give 1 for g_A^S. The relativistic effects reduce static prediction for g_A by a factor η

$$g_A^I = 5/3\,\eta \tag{3.1}$$

Experimental value $g_A^I = 1{,}25$ [23-25] is fitted with $\eta = 0.75$. As long as the flavor symmetry is unbroken, one finds a unique prediction valid for any quark model

$$g_A^S = \eta \sim 0.75 \tag{3.2}$$

Using the existing experimental values for the deep-inelastic scattering and with some theoretical extrapolation, Ioffe and collaborators[28] found out the value

$$g_A^S \sim 0.5 \tag{3.3}$$

This value is in good agreement with the theoretical estimate

$$g_A^S = 0.5 \pm 0.2 \tag{3.4}$$

which was obtained[28] in a nonperturbative QCD approach. Comparable result

$$g_A^S = 0.68 \pm 0.02 \tag{3.5}$$

has been found out[27] using SU(3) symmetry and parameters of hyperon semileptonic decays.

It has been shown[17,18] sometime ago that a correct value for g_A^I can be reproduced in a version of the chiral bag model in which the Wigner phase region does not coincide with the confinement region. This means that the pion field is not excluded from the bag at the confinement radius R but at a smaller radius R_{ch} corresponding to the length scale at which chiral sammetry is broken. This region $R_{ch} < r < R$ is so called skin (CBS model).

In general the axial vector formfactor has a quark and a meson contribution. The first one is of the form

$$g_A^Q(B_i \to B_f) = O(B_f, B_i) \int_0^R d^3r \left(U_i U_f - \frac{1}{3} v_i v_f\right) \tag{3.6}$$

The mesonic part of the axial vector current is of the form [16,19,20]

$$A_\mu^M(x) = -f_M \partial_\mu \phi^M(x) \tag{3.7}$$

Here M denotes one of the nonet (8 + 1) of mesons. The static [17,18] field ϕ^M is determined by the boundary condition at $r = R_{ch}$ and it satisfies the Klein-Gordon equation. This can be solved in terms of Green functions. The ratio g_A^S / g_A^I can be written in a compact form:

$$\frac{g_A^S}{g_A^I} = \frac{3}{5} \frac{1 - \frac{R_{ch}^2}{R}\left[\frac{1}{5}\Delta_1^{\eta_8} + \frac{4}{5}\Delta_1^{\eta_1}\right]}{1 - \frac{R_{ch}^2}{R}\Delta_1^{\pi}} \tag{3.8}$$

which openly displays symmetry breaking. With all meson masses μ_M equal, one finds the old SU(6) spin-flavor symmetry value 0.6. It is gratifying that the R-dependence is very weak and that the SU(3) (and/or U(3)) symmetry breaking due to the meson masses determines the result.

Similar structure holds quite generally

$$g_A(B_i \to B_f) = O(B_i, B_f)\, g_f \left[1 - \frac{R_{ch}^2}{R}\Delta_1^M(R_{ch}, R)\right] \tag{3.9}$$

The factor g_f is 0.654 for $\Delta S = 0$ transitions and 0.7115 or 0.730 for m_S = 0.2 GeV or 0.3 GeV for $\Delta S \neq 0$ transitions. Some interesting numerical values are displayed in Table III.

Table III

Transition	Without mesons $m_s = .2$	Without mesons $m_s = .3$	$R = 5.645\ GeV^{-1}$ $\mu_M = 0$ $m_s = .3$	$\mu_M \neq 0$ $m_s = .3$	Exp.
$\Sigma \to \Lambda$	0.534	0.534	0.613	0.599	0.595
$\Lambda \to p$	0.871	0.894	1.027	0.937	0.857
$\Xi^- \to \Sigma^0$	0.839	0.860	0.988	0.902	0.891
$\Xi^- \to \Lambda$	0.290	0.298	0.342	0.312	0.340
$\Sigma^- \to n$	0.237	0.243	0.279	0.255	0.310
$n \to p$	1.090	1.090	1.251	1.223	1.233

(Masses are in GeV. Experimental values are from ref. [24]. We used $R_{ch}/R = 2/3$)

It seems that CBS model gives reasonable agreement with experiments. The worst disagreement one finds for $g_A(\Sigma \to n)$ which is about 22%. Without SU(3) symmetry breaking the analysis[24] finds $g_A(\Xi^- \to \Lambda)/g_A(\Sigma^- \to n) \leq 1$, while the SU(3) symmetry breaking leads to $g_A(\Xi^- \to \Lambda)/g_A(\Sigma^- \to n) > 1$. Our SU(3) symmetry breaking mechanism supports the second alternative while an alternative SU(3) breaking theoretical scheme 29 would support the first possibility. All SU(3) breaking schemes are in trouble with the ratio $g_A(\Lambda \to p)/g_A(\Xi^- \to \Sigma^0)$ which always seem to come out too large. However, this ratio is only about 8 % wrong (1.03 instead 0.96), while the calculated absolute values in question are too large by about 9 % for $g_A(\Lambda \to p)$ and by about 1,2 % for $g_A(\Xi^- \to \Sigma^0)$. All other g_A values are relatively speaking in agreement with empirical values.

The absolute magnitude of the mesonic terms decreases with the increase of the meson mass μ_M. This was the mechanism which made the ratio (3.8) smaller than 0.6 as it should be. The usefulness of the same mechanism can be also seen from Table III. The constants g_A corresponding to the $\Delta S \neq 0$ hyperon decays are smaller relative to $\Delta S = 0$ coupling constants when $\mu_M \neq 0$. That effect, which is due to $\mu_K > \mu_\pi$, improves the agreement with the empirical data. An important test for the model is the determination of the isoscalar g_A^S coupling constant.

4. Compositeness of the W Intermediate Vector Boson

Both the center-of-mass corrections [30] (CMC) and the recoil corrections (RC) (which have been studied in the section 2) influence the calculation of the nuclear form factors based on a static model for the confinement of quarks [31,32]. The formalism which was developed for the calculation of CMC can be also used to estimate confinement radii of the composite vector bosons [32].

There exists a class of composite models [33, 34] in which in analogy with the ρ -meson pole dominance the weak amplitudes at low energies are dominated by poles which can be identified with composite weak bosons (W). The matrix element of a weak current depends on the W-boson coupling constant

$$f_W - \frac{e}{\sin\Theta_W} \cong 0.66 \qquad (4.1)$$

in the same way as the isovector current matrix element depends on f_ρ coupling constant

$$\langle 0| j_\mu(0)|0,\alpha\rangle = \varepsilon_\mu \frac{M_\alpha^2}{f_\alpha} \qquad (4.2)$$

There exists a complete formal analogy between the weak and the strong isospin algebra and between internal structures of W and ρ mesons [39,34]. The role played by quarks in one case is played by the subconstituents in the other case. It is thus natural to assume a baglike model ["bag" being produced by the action of the quantum hyper-color dynamics (QHD)] for the description of W bosons. It has been shown already [31,32] that such a simple model, with center-of-mass corrections (CMC), can describe a composite electron and its magnetic moment. As the magnitude of CMC depends on the confinement radius R, The same model can describe a proton. Theory gives reasonable values for g_A and μ , and also for μ_e (electron magnetic moment) [32]. In the latter case confinement radius is about 10^3 times smaller than the one used for the proton bag. The model used to calculate CMC gives small corrections for proton mass, while allowing for the small composite electron mass[32]. It does not get into great difficulties with either proton or electron charge radii[32]. Without going into the questions of the deeper theoretical justification, or in the problems of the existence of the compositeness at the radii 10^3 smaller than proton-bag radius, one can apply the formalism as a semiempirical algorithm to the W-boson-ρ-meson situation, and calculate coupling constants f_ρ and f_W as functions of vector-boson masses, confinement radii, and model constants. The boson masses can also be explained inside the framework of the model. It is based on decomposition of a static composite bag state $|\vec{r}\rangle_\alpha$ into components Φ (k) [30].

$$|\vec{r}\rangle_\alpha = \int d^3k \, e^{i\vec{k}\cdot\vec{r}} \phi(k) \, W^{-1}(k) \, |\vec{k},\alpha\rangle \tag{4.3a}$$

Here

$$W(k) = 2\sqrt{k^2 + M_\alpha^2}$$

$$\phi(k) = [W(k) I(k) / (2\pi)^3]^{1/2} \tag{4.3b}$$

$$I(k) = \frac{1}{(2\pi)^3} \int d^3r \, e^{-i\vec{k}\cdot\vec{r}} \, {}_\alpha\langle 0|\vec{r}\rangle_\alpha$$

The Hill-Wheeler overlap function can be approximated by [30].

$${}_\alpha\langle 0|\vec{r}\rangle_\alpha = T(r) = \left[e^{-r^2/4R_0^2} \left(1 - C\frac{r^2}{R_0^2} \right) \right]^2$$

$$C = \beta^2/(4+6\beta^2) \tag{4.3c}$$

The parameter R_0 is connected to the bag radius R by

$$R^2 = \frac{3}{2} R_0^2 \left[\frac{1 + 5/2\,\beta^2}{1 + 3/2\,\beta^2} \right]$$

The parameter β ($\beta = 0.36$ for a hadron bag) determines the probability that the constituent is in the relativistic or "lower" component of the model wave function. Further details can be found in Ref.[30]. The integral over the static-model value of the current matrix element is

$$\vec{\varepsilon} S = \int d^3r \langle 0|\vec{j}(r)|\vec{r}\rangle_\alpha = \int d^3r \int d^3k\, W^{-1}(k)\phi(k) e^{i\vec{k}\cdot\vec{r}} =$$
$$= (2\pi)^3 W^{-1}(0)\, \phi(0) \langle 0|\vec{j}(0)|0,\alpha\rangle =$$
$$= (2\pi)^3 W^{-1}(0)\phi(0)\, \vec{\varepsilon}\, M_\alpha^2 / f_\alpha \tag{4.4}$$

The quantity S is the value of the bag-model matrix element

$$S = \frac{1 - \beta^2/2}{1 + 3\beta^2/2} \tag{4.5}$$

From (4.4) one finds the expression for the coupling constant

$$f_\alpha = \frac{(2\pi)^{3/4}\, K}{\sqrt{2}\, S}\, M_\alpha^{3/2} R_{\alpha 0}^{3/2} \tag{4.6}$$

$$K = (1 - 6C + 15C^2)^{1/2}$$

Here $R_{\alpha 0}$ is a confinement radius. With β = 0.36, $R_{\alpha 0}$ = 0.65 fm, one finds f_ρ = 13.3, which is only about twice as large as the experimental value f_ρ = 5.3-5.6. This discrepancy is similar to the one found in Ref.[30] for the pion form factor and it is not too bad considering that $I(0)$ has been estimated using approximate wave functions. An acceptable f_W follows only if $R_{W0} \ll R_{\rho 0}$. One can derive an approximate relation between confinement radii, and coupling constants,

$$\frac{R_{W0}^{3/2}\, M_W^{3/2}}{f_W} = \frac{R_{\rho 0}^{3/2}\, M_\rho^{3/2}}{f_\rho}\, \eta \tag{4.7}$$

$$\eta = S(\beta_W)\, S^{-1}(\beta_\rho)(1 - 6C_\rho + 15C_\rho^2)^{1/2}(1 - 6C_W + 15C_W^2)^{1/2}$$

The value of η is close to unity. By using the value(4.1)for f_W, η = 1, and experimental values dor other quantities, one finds

$$R_W / R_\rho \cong 2 \times 10^{-3} \tag{4.8}$$

Although this composite model of the W boson is quite crude and simple, it does seem to incorporate naturally a small confinement radius (10^{-16}cm) and connects it to the empirical coupling constant and mass. This fact could encourage speculations about spinorial subconstituents of the weak W boson which are bound by a QCD-like force [35].

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