WIS-PH--90/43

WIS-90/43-PH

Masses, Magnetic Moments, QCD and Proton Spin Structure

Harry J. Lipkin
Department of Nuclear Physics
Weizmann Institute of Science
Rehovot 76100, Israel
and
School of Physics and Astronomy
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University
Tel Aviv, Israel

Submitted to Proceedings of the X International Seminar on
High Energy Physics Problems, Relativistic Nuclear Physics
and Quantum Chromodynamics, Dubna, USSR, Sept. 24-29, 1990

October 29, 1990

ABSTRACT

This talk is dedicated to the memory of Andrei D. Sakharov. In addition to hos well-known contributions to society, Sakharov was also a pioneer in spin physics and the application of the basic ideas of QCD to the spin structure of hadrons. He took quarks seriously at the time when the particle physicists ridiculed the quark model. Immediately after the quark proposal Sakharov asked: "Why is $M_\Lambda \neq M_\Sigma$? They contain the same quarks." His answer was "Spin Physics! A flavor-dependent hyperfine interaction" [1]

I. The Extended and Updated Sakharov-Zeldovich Model

In 1966 Sakharov and Zeldovich [2]. *anticipated* QCD by assuming that all the flavor dependence in the two-body interaction was in a flavor-dependent hyperfine interaction

$$v_{ij} = v^o_{ij} + \vec{\sigma}_i \cdot \vec{\sigma}_j v^{hyp}_{ij} \tag{1.1}$$

where v^o_{ij} is independent of spin and flavor, $\vec{\sigma}_i$ is a quark spin operator and v^{hyp}_{ij} is the strength of the hyperfine interaction which is flavor-dependent and has different strengths for quark-quark and quark-antiquark interactions but is assumed to have the same flavor dependence. They obtained two relations between meson and baryon masses in surprising agreement with experiment [2, 3].

$$m_s - m_u = M_\Lambda - M_N = 177\,\text{MeV} = \frac{3}{4}\left(M_{K^*} - M_\rho\right) + \frac{1}{4}\left(M_K - M_\pi\right) = 180\,\text{MeV}. \tag{1.2a}$$

$$1.53 = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61 = \frac{v^{hyp}_{ud}}{v^{hyp}_{us}} \tag{1.2b}$$

where the subscripts u, d and s refer to quark flavors. This striking evidence that mesons and baryons are made of the same quarks was overlooked for amusing reasons [4, 5]. and rediscovered in 1978 [6].

Any realistic hadron model must keep this universality of mesons and baryons. For example, if there are strange quarks in the nucleon there must also be strange quarks in the π and ρ mesons.

Input from QCD that the hyperfine interaction is produced by one gluon exchange explained the sign of the $\Delta - N$ and $\rho - \pi$ mass splittings [7] and led to a successful prediction for μ_Λ obtained before the experiment [7] by assuming that the ratio of the quark magnetic moments μ^{EM}_s/μ^{EM}_d is the same as that of the corresponding color magnetic moments which produce the hyperfine splittings,

$$\mu_\Lambda = -0.61\,\text{n.m.} = -\frac{\mu_p}{3}\frac{\mu^{EM}_s}{\mu^{EM}_d} = -\frac{\mu_p}{3}\frac{\mu^{col}_s}{\mu^{col}_d} = -\frac{\mu_p}{3}\frac{M_{\Sigma^*} - M_\Sigma}{M_\Delta - M_N} = -0.61\,\text{n.m.} \tag{1.3}$$

where μ^{col}_f denotes the color magnetic moment of a quark of flavor f.

Further input from QCD suggests that the hyperfine interaction is inversely proportional to the product of the masses of the interacting quarks [7] and otherwise flavor independent.

$$v^{hyp}_{ij} = \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j}\tilde{v}_{ij}. \tag{1.4}$$

where m_i is an effective quark mass and $\tilde{v}_{ij}$ is flavor independent. This input was used by Sakharov, working alone in Gorkii, to obtain additional mass relations[3]. Cohen and

Lipkin [8] introduced the additional assumption that the same quark mass parameters appear in the additive mass terms in the Hamiltonian (1.1) and that these include not only the full single particle energy ϵ_i including the kinetic energy but also the flavor-independent part of the two-body interaction; i.e.

$$\sum_i m_i = \sum_i \epsilon_i + \sum_{i>j} v^o_{ij} \tag{1.5a}$$

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j} v_{ij}. \tag{1.5b}$$

Although the extreme assumption (1.5a) seems highly questionable, the relation (1.5b) has described hadron masses and magnetic moments with remarkable success. The success of this model remains to be understood at a more fundamental level. Some indications of the underlying physics has been given in one simple model [8] which shows that the effective mass includes to a good approximation some relativistic corrections, kinetic energies and potential energies due to flavor and spin-independent effective quark-quark and quark-antiquark interactions related by the standard color factor of two [9, 10]. These conclusions have been further supported by a variational treatment which shows that relations between baryon and meson masses are obtained as inequalities by using the exact three-body baryon wave function as a trial wave function for the meson case, and rescaling the wave function to satisfy the virial theorem [11].

To obtain nontrivial significant tests of the model we avoid taking credit for duplicating known mass formulas like Gell-Mann-Okubo which arise as good approximations in almost any model. Real tests of the model are obtained by considering only nine hadron masses not related by these simple formulas; those of the five baryons and four mesons in the ground state configuration which contain no more than one strange quark. Since the formula (1.5b) has four free parameters, the two quark masses and the two interaction strength parameters v_{ij} for mesons and baryons, there are five independent relations. Assuming that the hyperfine interaction is inversely proportional to the same effective mass parameter m_i appearing in the first term of (1.5b) gives two new relations, one with only baryons and one with only mesons [12].

$$m_s - m_u = M_\Lambda - M_N = 177\,\text{MeV} = \frac{M_N + M_\Delta}{6} \cdot \left(\frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} - 1 \right) = 190\,\text{MeV}. \tag{1.6a}$$

$$m_s + m_u = \frac{3M_{K^*} + M_K}{4} = 793\,\text{MeV} =$$

$$= \frac{3M_\rho + M_\pi}{8} \cdot \left(\frac{M_\rho - M_\pi}{M_{K^*} - M_K} + 1 \right) = 791\,\text{MeV}. \tag{1.6b}$$

The remaining three relations are well known and included the two Sakharov-Zeldovich relations (1.2a) and (1.2a).

We also note three predictions of hadron magnetic moments with no free parameters; namely (1.3) and

$$-1.46 = \frac{\mu_p}{\mu_n} = -\frac{3}{2} \tag{1.7a}$$

$$\mu_p + \mu_n = 0.88\,\text{n.m.} = \frac{2M_p}{M_N + M_\Delta} = 0.865\,\text{n.m.} \tag{1.7b}$$

The well-known prediction for the ratio of the nucleon magnetic moments (1.7a) follows from the assumption that hadron magnetic moments are obtainable from the constituent quark wave functions with quark magnetic moments proportional to their electric charges. The relation (1.7b) was obtained by using Dirac moments for the quarks with effective quark masses determined from hadron masses and the first term of eq. (1.5b) [13, 14]. The agreement with experiment of this prediction expressing a magnetic moment with a scale determined entirely by masses with no free parameters is impressive.

II. The Implications of the Experimental Values of G_A/G_V

The spin structure of the proton presents an interesting interface between particle and nuclear physics. Nuclear physicists measure G_A/G_V. Particle physicists don't understand the basic physics of G_A/G_V. Nuclear physicists have seen the beta decay of polarized neutrons and knw that the spin-flip amplitude is large! Particle physicists tend to ignore the inconsistency between this large spin-flip amplitude and the interpretation of the EMC experiment that all the spin of the proton is carried by degrees of freedom that are spectators in neutron decay.

The recent analysis of the EMC experiment and weak decays with its surprising conclusion [15] of zero quark spin contribution to the proton spin has been questioned because of their use of SU(3) symmetry [16]. The weak decays, unlike the EMC experiment, do not directly measure linear combinations of the fractional contributions of the u, d and s - flavored current quarks and antiquarks respectively to the spin of the proton conventionally denoted by $\Delta u(p)$, $\Delta d(p)$ and $\Delta s(p)$. They measure flavor changing transition matrix elements which depend upon the wave functions of both the initial and final states, and which can be related by symmetry assumptions to quark contributions to the spins of the initial and final states [17]. Conventional SU(3) analyses assume SU(3) flavor symmetry both for the weak currents and the hadron wave functions. With these assumptions the experimental results for the $\Sigma^- \rightarrow n$ semileptonic weak decay and the neutron beta decay [18] immediately give information about $\Delta u(p)$, $\Delta d(p)$ and $\Delta s(p)$.

$$(G_A/G_V)_{(n\rightarrow p)} = \Delta u(p) - \Delta d(p) = \Delta d(n) - \Delta u(n) = 1.259 \pm 0.004 \tag{2.1a}$$

$$(G_A/G_V)_{(\Sigma^-\to n)} = \Delta s(\Sigma^-) - \Delta u(\Sigma^-) = \Delta u(n) - \Delta s(n) =$$

$$= \Delta d(p) - \Delta s(p) = -0.328 \pm 0.019 \tag{2.1b}$$

The relation (2.1a) assumes only isospin symmetry which is generally considered to be valid. The relation (2.1b) is open to question because it assumes that nucleon and hyperon wave functions are identical except for flavor change. We therefore examine the experimental result (2.1b) directly in terms of the flavor-changing transition matrix elements. We first note two remarkable features of this transition:

1. The experimental result [18] $G_A/G_V = -0.328 \pm 0.019$ is in surprising agreement with the naive SU(6) prediction $G_A/G_V = -1/3$.
2. The transition $\Sigma^- \to n$ is uniquely simple. It involves only the transition of a single "active" s quark in the Σ^- into a u quark in the neutron, with all the remaining degrees of freedom, including all the d quarks remaining inert spectators.

We can therefore write wave functions for describing this decay by separating the degrees of freedom into the spin of the active quark, s in the Σ^-, u in the neutron, and the spectator degrees of freedom, denoted by S, which can be any combination of d quarks, quark-antiquark pairs, gluons and orbital angular momenta. Since the active quark spin and the baryon total angular momentum in its rest frame are both one-half, there are only two allowed values, zero and one for the spectator angular momentum in the rest frame. The wave functions can therefore each be written as the sum of two terms, with a relative strength defined by a parameter conveniently written as a mixing angle denoted by θ^Σ and θ^n respectively,

$$|\,\Sigma\rangle = \cos\theta^\Sigma \,|\, S_1^\Sigma; s\rangle + \sin\theta^\Sigma \,|\, S_o^\Sigma; s\rangle \tag{2.2a}$$

$$|\,n\rangle = \cos\theta^n \,|\, S_1^n; u\rangle + \sin\theta^n \,|\, S_o^n; u\rangle \tag{2.2b}$$

where S_o^Σ, S_1^Σ, S_o^n and S_1^n denote the spectator states in the Σ and neutron with angular momentum zero and one respectively. Note that the terms with spectators having angular momentum one include the SU(6) wave function in which the only other degrees of freedom carrying angular momentum are the two spectator d quarks which are coupled to angular momentum one.

The value of $(G_A/G_V)_{(\Sigma^-\to n)}$ is easily calculated by noting that both the vector and axial transition matrix elements are equal to unity for a single quark transition. Thus the only matrix element that differs from unity is the axial matrix element for the state with the spin-one spectator where the active quark has an average spin contribution of -1/3. Thus we can write

$$(G_A/G_V)_{(\Sigma^-\to n)} = \frac{-(1/3)+\xi}{1+\xi} = -\frac{1}{3}\cdot\frac{1-3\xi}{1+\xi} = -0.328 \pm 0.019 \tag{2.3a}$$

where

$$\xi = \tan\theta^{\Sigma}\tan\theta^{n} \cdot \frac{\langle S_o^n \mid S_o^{\Sigma}\rangle}{\langle S_1^n \mid S_1^{\Sigma}\rangle} \tag{2.3b}$$

This contrasts with the neutron decay, where there are two active d quarks in the neutron and two active u quarks in the proton, either pair of active quark spins can be coupled to spin zero or spin one, and there are many more free parameters depending upon the wave functions in the expression for $(G_A/G_V)_{(n\to p)}$.

Note that in the SU(3) symmetry limit the two mixing angles are equal and all the spectator overlaps are unity. One therefore expects that the parameter ξ remains positive even when SU(3) is broken, since one expects the symmetry breaking to affect the relative magnitudes of the two components in the wave functions but not to reverse the relative phase. We therefore find that the SU(6) value -(1/3) is an extremum, and that the experimental value is at this extremum.

Thus in any model where the baryon octet wave functions satisfy SU(3) symmetry and all the isospin of the nucleon is carried by three valence quarks; i.e. any sea of quark-antiquark pairs present is isoscalar, the contributions to the nucleon spin from the odd-flavored valence quark are given by

$$\Delta u^v(n) = \Delta d^v(p) = -0.328 \pm 0.019 \approx -1/3 \tag{2.4a}$$

while the experimental result from neutron beta decay gives

$$\Delta u^v(p) - \Delta d^v(p) = \Delta d^v(n) - \Delta u^v(n) = 1.259 \pm 0.004 \approx 5/4 \tag{2.4b}$$

where we have used the notation of Ramsey et al [19] and decomposed the quantities $\Delta u(p)$, $\Delta d(p)$ and $\Delta s(p)$ into valence and sea contributions denoted by the superscripts v and s respectively. Thus

$$\Delta u^v(p) = \Delta d^v(n) \approx 11/12 \tag{2.5a}$$

$$\Delta u^v(p) + \Delta d^v(p) \approx 7/12 \tag{2.5b}$$

However, we also note that the nucleon wave function (2.2b) immediately gives the result

$$\Delta u^v(n) = \Delta d^v(p) = -\frac{1}{3}\cdot(\cos^2\theta^n - 3\sin^2\theta^n) = -\frac{1}{3}\cdot(1 - 4\sin^2\theta^n) \tag{2.6}$$

We now look for a wave function which satisfies the results (2.4a) and (2.6), which give the SU(6) value and imply that $\sin^2\theta^n \approx 0$ and also the result (2.4b) which implies that SU(6) breaking is appreciable, and reduces $\Delta u^v(p) - \Delta d^v(p)$ by a factor of 3/4 from the SU(6) value. This implies breaking SU(6) in a way which does not change the spin coupling of the active quark in the $\Sigma^- \to n$ decay. The experimental result (2.3a) for $(G_A/G_V)_{(\Sigma^-\to n)}$ requires a neutron wave function where the degrees of freedom which are spectators in the $\Sigma^- \to n$ transition are coupled to total angular momentum one and the spin of the active u quark satisfies the relation (2.4a) to have $\Delta u^v(n) = \Delta d^v(p) \approx -1/3$. The neutron beta decay result requires the quark spins to satisfy the relation (2.4b) which leads to the value (2.5a) for the contributions of the two quarks of the same flavor to the nucleon spin, $\Delta u^v(p) = \Delta d^v(n) \approx 11/12$.

Nucleon wave functions which satisfy these conditions can be found by examining the list of spin expectation values for all possible couplings of three valence quarks to everything else to made a spin-$\frac{1}{2}$ proton [20]. There are three states with $\Delta u^v(n) = \Delta d^v(p) = -1/3$. Since this value is an extremum, only mixtures of these three states need be considered. We then look for mixtures which give the desired value $\Delta u^v(p) = \Delta d^v(n) \approx 11/12$. The values of $\Delta d^v(n)$ for these states are[20]

$$\langle S_d = 1; X = 0 \mid \Delta d^v(n) \mid S_d = 1; X = 0\rangle = 4/3 \tag{2.7a}$$

$$\langle S_d = 1; X = 2 \mid \Delta d^v(n) \mid S_d = 1; X = 2\rangle = -2/3 \tag{2.7b}$$

$$\langle S_d = 0; X = 1 \mid \Delta d^v(n) \mid S_d = 0; X = 1\rangle = 0 \tag{2.7c}$$

where S_d denotes the total spin of the d quarks in the neutron and X denotes the total angular momentum of the other degrees of freedom which are spectators in the weak decays. The desired neutron wave function can be written as a linear combination of these states:

$$\mid n\rangle = C_{10} \mid S_d = 1; X = 0\rangle + C_{12} \mid S_d = 1; X = 2\rangle + C_{01} \mid S_d = 0; X = 1\rangle \tag{2.8a}$$

where the coefficients C_{10}, C_{12} and C_{01} satisfy the conditions

$$|C_{10}|^2 + |C_{12}|^2 + |C_{01}|^2 = 1 \tag{2.8b}$$

$$(4/3)|C_{10}|^2 - (2/3)|C_{12}|^2 = 11/12 \tag{2.8c}$$

Any wave function satisfying these conditions will give agreement with both (2.5a) and (2.5b), thus agreeing with the experimental values of G_A/G_V for both transitions. The state $\mid S_d = 1; X = 0\rangle$ is the conventional SU(6) wave function which is totally symmetric under both spatial permutations and flavor-spin and has all the nucleon spin carried by valence quarks. From eq. (2.8c) we obtain a lower bound on the coefficient of this state in the neutron wave function

$$|C_{10}|^2 \geq= 11/16 \tag{2.9}$$

Thus the SU(6) wave function is required to be about 3/4 of the total wave function which is compatible with the observation that the value of G_A/G_V must be reduced by a factor 3/4 from the SU(6) value to give agreement with experiment.

We can also fit the experiments by breaking SU(3) and setting

$$\langle S_o^n \mid S_o^\Sigma \rangle \approx 0 \tag{2.10a}$$

and

$$\sin^2\theta^n \approx 1/16 \tag{2.10b}$$

This satisfies both experimental requirements (2.3a) and (2.4b) at the price of making the SU(6) breaking admixtures to the wave function very different in the nucleon and the Σ. This however, is quite reasonable, since all proposed dynamical models for SU(6) symmetry breaking also introduce large SU(3) breaking[17].

This again suggests that fitting hyperon data by breaking SU(6) and keeping SU(3) with the usual D/F fudge factor has no physical basis.

III. Nucleon Magnetic Moments and G_A/G_V

The nucleon magnetic moments are given by the simple formulas

$$\mu_p = K\langle +\frac{2}{3}\cdot(L_{zu}+2S_{zu}) - \frac{1}{3}\cdot(L_{zd}+2S_{zd})\rangle_p \tag{3.1a}$$

$$\mu_n = K\langle -\frac{1}{3}\cdot(L_{zu}+2S_{zu}) + \frac{2}{3}\cdot(L_{zd}+2S_{zd})\rangle_p \tag{3.1b}$$

where K is a constant and L_{zu}, L_{zd}, S_{zu} and S_{zd})denote the z-components of the orbital and spin angular momenta of all the u-quarks and all the d-quarks respectively in the proton. In this notation it is convenient to rewrite eq. (2.1a)

$$(G_A/G_V)_{(n\to p)} = \Delta u(p) - \Delta d(p) = 2\langle S_{zu} - S_{zd}\rangle_p = 1.259 \pm 0.004 \tag{3.2a}$$

and define

$$\rho_\mu \equiv \frac{1}{3}\cdot\frac{\mu_p-\mu_n}{\mu_p+\mu_n} = 1.78 \tag{3.2b}$$

Both G_A/G_V and ρ_μ are predicted to be 5/3 in the SU(6) model. Then from eqs. (3.1) and (3.2) we obtain

$$\Delta u(p) + \Delta d(p) = \frac{1}{\rho_\mu}\cdot(G_A/G_V)_{(n\to p)}\cdot\left(1 - \frac{(\rho_\mu^2-1)\cdot\xi}{\rho_\mu - \xi}\right) \tag{3.3a}$$

where ξ is defined as

$$\xi \equiv \frac{\frac{\langle L_{zu}\rangle}{\langle S_{zu}\rangle} - \frac{\langle L_{zd}\rangle}{\langle S_{zd}\rangle}}{4\cdot\left(1 + \frac{\langle L_{zu}\rangle}{\langle S_{zu}\rangle} + \frac{\langle L_{zd}\rangle}{\langle S_{zd}\rangle}\right)} \tag{3.3b}$$

We note that ξ is small in nearly all models. It is zero in all models where $L = 0$ and also the relativistic MIT bag model where the numerator of the RHS of eq. (3.3b) vanishes. Substituting the experimental values (3.2) then gives

$$\Delta u(p) + \Delta d(p) = 0.7 \cdot \left(1 - \frac{1.22\xi}{1 - 0.56\xi}\right) \tag{3.4}$$

Thus 70% of the proton spin is carried by valence quarks in any model that fits both G_A/G_V and ρ_μ and has a small value for ξ.

IV. A Toy Model for the Proton with One Gluon

Consider a wave function for a proton which mixes a 3qG state of three quarks and a gluon with a 3q state, [21].

$$| p \uparrow\rangle = \cos\theta \mid (3q)_{1;I=I_z=S=S_z=1/2}\rangle + \sin\theta \mid \{(3q)_{8;I=I_z=S_q=1/2}G\}_{J=J_z=1/2}\rangle \tag{4.1}$$

where the subscripts 1 and 8 denote the color coupling of the three quarks to color singlet and color octet, we assume that the spins S_q of the three quarks in the $3q$ state are coupled to $S_q = 1/2$, and θ is a mixing angle parameter which specifies the amount of mixing. The value of this free parameter is fixed by fitting the experimental value G_A/G_V.

$$G_A/G_V = 2\langle p \uparrow\mid S_{zu} - S_{zd} \mid p \uparrow\rangle = (5/3)\cos^2\theta - (1/9)\sin^2\theta = 1.259 \pm 0.004 \approx 5/4 \tag{4.2a}$$

$$\sin^2\theta \approx 15/64 \tag{4.2b}$$

The question then arises what are the magnetic moments. The ratio $\frac{\mu_p}{\mu_n}$ turns out to be

$$\frac{\mu_p}{\mu_n} \approx -\frac{71}{49} = -1.45 \tag{4.3}$$

This is much closer to the experimental value -2.79/1.91 = -1.46 than the $SU(6)$ value. Thus the admixture not only fits G_A/G_V, it *improves* the fit to the magnetic moment ratio.

The wave function (4.2) has an appreciable fraction of the proton spin carried by the glue. The fraction of the proton spin carried by the three valence quarks is given by

$$2\langle p \uparrow\mid S_{zv} \mid p \uparrow\rangle = 2\langle p \uparrow\mid S_{zu} + S_{zd} \mid p \uparrow\rangle = \cos^2\theta - (1/3)\sin^2\theta \approx 11/16 = 0.69 \tag{4.4}$$

Thus only about 70% of the proton spin is carried by valence quarks in agreement with eq. (3.4).

V. The Implications of the EMC Result

Brodsky, Ellis and Karliner [15] give

$$\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s = 0.246 \pm 0.026 \pm 0.056 \tag{5.1}$$

while

$$(G_A/G_V)_{(n\to p)} = \Delta u(p) - \Delta d(p) = \Delta d(n) - \Delta u(n) = 1.259 \pm 0.004 \tag{2.1a}$$

Rearranging these gives

$$\Delta u + \Delta d + \Delta s = -0.02 + 0.13\eta \pm 0.12 \pm 0.25 \tag{5.2a}$$

where η is the deviation from SU(6), defined by the relation

$$\Delta d - \Delta s = -(1/5)(\Delta u - \Delta d)(1+\eta) \tag{5.2b}$$

The correction term 0.13η is seen to be small in all models. For example, using SU(3) and hyperon data,as in eqs. (2.1), $\eta = 1/3$ and $0.13\eta = 0.04$. Thus if we accept the quark-parton model and its naive interpretation [15]

$$\Delta u + \Delta d + \Delta s \approx 0. \tag{5.3}$$

BEK suggest the values:
$\Delta u = 0.74$; $\Delta d = -0.51$; $\Delta s = -0.23$;
If we split this into valnece + sea quarks, note that there are no valence strange quarks and assume an SU(3)-symmetric sea,
$\Delta u_s = \Delta d_s = \Delta s = -0.23$; $\Delta u_v = 0.97$; $\Delta d_v = -0.28$; $\Delta u + \Delta d = 0.69 \approx 0.70$
It is interesting that this is the same as the value obtained in eq.(4.3) from completely different considerations.

VI. Conclusions

The systematics of hadron spin structure pose an interesting challenge for QCD.

1. Masses and magnetic moments are fit by a very simple quark model with $|\,qqq\rangle$ and $|\,q\bar{q}\rangle$ and NOTHING ELSE! The effective masses include kinetic and potential energies. But what are the quarks in this model? Quasiparticles?

2. Weak decays. G_A/G_V described by electroweak current quarks. $(G_A/G_V)_{(n\to p)} > 1$ but disagrees with $SU(6)$, while $(G_A/G_V)_{(\Sigma^-\to n)}$ is in excellent agreement.

3. EMC. The spin dependence of e^-p scattering gives a much lower cross section than expected from a simple quark-parton model and suggests that $\Delta u + \Delta d + \Delta s \approx 0$!

References

1. Andrei D. Sakharov, Autobiography
2. Ya. B. Zeldovich and A.D. Sakharov, Yad. Fiz 4 (1966) 395; Sov. J. Nucl. Phys. 4 (1967) 283
3. A. D. Sakharov, Pisma JETP 21 (1975) 554; JETP 78 (1980) 2113 and 79 (1980) 350
4. Harry J. Lipkin, in Gauge Theories, Massive Neutrinos and Proton Decay (Proceedings of Orbis Scientiae 18th Annual Meeting, Coral Gables, Florida, 1981) edited by Behram Kursonoglu and Arnold Perlmutter (Plenum, N.Y., 1981), p. 359
5. A. D. Sakharov, private communication; Harry J. Lipkin, Annals of the New York Academy of Sciences 452 (1985) 79, and London Times Higher Education Supplement, January 20 (1984), p.17
6. Harry J. Lipkin, Phys. Lett. **B74** (1978) 399
7. A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. D12 (1975) 147
8. I. Cohen and H. J. Lipkin, Phys. Lett. 93B, (1980) 56
9. H.J. Lipkin, Phys. Lett. 45B (1973) 267
10. H. J. Lipkin, Phys. Lett. 171B, 293 (1986)
11. H. J. Lipkin, Phys. Lett. 172 (1986) 242
12. Harry J. Lipkin, Phys. Lett. **B233** (1989) 446; Nuc. Phys. A507 (1990) 205c
13. Harry J. Lipkin, In: Proceedings of the 7th International Symposium on High Energy Spin Physics, Protvino (USSR), 22-27 September, (1986) Edited and Published by The Institute of High Energy Physics, Serpukhov (USSR), (1987) Vol. I, p.98
14. Harry J. Lipkin, Nucl. Phys. A478, (1988) 307c
15. Stanley J. Brodsky, John Ellis and Marek Karliner, Phys. Lett. 206B, 309 (1988)
16. Harry J. Lipkin, Phys. Lett. B214 (1988) 429
17. Harry J. Lipkin, Phys. Lett. B230 (1989) 135
18. Particle Data Group, Phys. Lett. B239 (1990) 1
19. G. Ramsey et al Phys. Rev. D39, 361 (1989)

20. Harry J. Lipkin, Phys. Lett. B237 (1990) 130

21. Harry J. Lipkin, G_A/G_V, Argonne preprint ANL-HEP-PR-90-64 Physics Letters, In Press