Quarks in Hadrons and Nuclei

(Applications of the NJL Model)

- Part I: Quarks and Mesons -

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**Introduction**

**Q1**: What is the Nambu-Jona-Lasinio (NJL) model?  
**A1**: A quark model based on relativistic field theory. Characteristic: Contact interactions between quarks. Easy to handle, very successful to describe hadrons, nuclear matter and quark matter.

**Q2**: Who invented this model?  
**A2**: Nambu and Jona-Lasinio in 1960, as a model for elementary nucleons. Re-discovered in the 1980th as a model for quarks.

**Q3**: What is this model good for?  
**A3**: We can describe

- hadrons (nucleons, mesons) as bound states of quarks
- nuclear matter and nuclei in terms of quarks (⇒ Quark nuclear physics; Medium modifications)
- phases of strongly interacting matter at high densities (⇒ Neutron stars, supernova matter)
Success of constituent quark model. Basic inputs are: Nonrelativistic quarks ($M_u \simeq M_d \simeq 300 - 400$ MeV), and symmetry of wave functions. But: Quarks of QCD are almost massless ($m \simeq 0$) and relativistic, and structure of wave functions should emerge from dynamics. ⇒ Generate constituent quark masses and wave functions dynamically from interactions.

The Lagrangian of any quark model should be symmetric under the global gauge transformations

$$\psi(x) \rightarrow e^{i\alpha} \psi(x), \quad \psi(x) \rightarrow e^{i\vec{\alpha} \cdot \vec{\tau}} \psi(x)$$

where $\psi = (\psi_u, \psi_d)$ is the flavor SU(2) quark field. ⇒ conserved currents $j^\mu = \bar{\psi} \gamma^\mu \psi$ and $\vec{j}^\mu = \bar{\psi} \gamma^\mu \vec{\tau} \psi$.

The interaction Lagrangian should also be symmetric under the chiral $SU_A(2)$ transformation

$$\psi(x) \rightarrow e^{i\vec{\alpha} \cdot \vec{\tau} \gamma_5} \psi(x)$$

If only the quark mass term $-m\bar{\psi} \psi$ breaks this symmetry, we are led to the PCAC relation:

$$\partial_\mu (\bar{\psi} \gamma^\mu \gamma_5 \vec{\tau} \psi) = 2m \bar{\psi} i \gamma_5 \vec{\tau} \psi.$$
Motivations: Symmetries (2)

- This chiral symmetry should be **spontaneously broken** and the pion should emerge as a **Goldstone boson**.

The above chiral $SU_A(2)$ transformation can be expressed as a rotation in the plane of $\sigma = \bar{\psi}\psi$ and $\vec{\pi} = \bar{\psi}i\gamma_5\vec{\tau}\psi$:

If the energy of the system along a circle is lower than at the origin ($\sigma = \pi = 0$), we may choose one of the states on the circle as the “**vacuum**”. (In the figure: $\sigma \neq 0$, $\pi = 0$.) A small chiral rotation (moving up along the circle) leads to another (degenerate) vacuum, which differs from the original one by the appearance of a $\pi$ field $\Rightarrow \pi$ is a massless “Goldstone boson”.

- The chiral $U_A(1)$ symmetry $\psi \rightarrow \exp(i\alpha\gamma_5)\psi$ is unwanted (no isoscalar Goldstone boson is observed!), and should be broken explicitly by the interaction.
Motivations: Interaction (1)

- How to model the elementary **qq interaction**? By meson exchange, like the nuclear force?
  - **But**: Mesons are also composite particles!
  - \( \Rightarrow \) Meson exchange between quarks should be the **result**, but not the **input** of the model.

- QCD based Dyson-Schwinger (and also some lattice) calculations indicate: qq interaction looks like gluon exchange, but with a modified "**running coupling**" \( \alpha_s(k) \):

\[
V(k) = \frac{\lambda^a}{2} \gamma^\mu \left( \frac{\alpha_s(k)}{k^2} \right) \gamma^\mu \frac{\lambda^a}{2}
\]

**Fig.1**

**qq interaction at low momenta**
Interaction and Lagrangian

Interaction is very strong at small $k$: **Infrared enhancement.**

⇒ For low momenta ($k < \Lambda \simeq 1$ GeV) we may approximate

$$\frac{\alpha_s(k^2)}{k^2} \rightarrow G \cdot \theta(\Lambda - k)$$

where $G$ is a 4-Fermi coupling constant. This looks like a contact interaction, but restricted to low momenta!

Using the flavor SU(2) quark field $\psi = (\psi_u, \psi_d)$, we can write the corresponding **Lagrangian density** as

$$\mathcal{L} = \overline{\psi} \left( i \not\nabla - m \right) \psi - G \left( \overline{\psi} \frac{\lambda^a}{2} \gamma_\mu \psi \right)^2$$

From Wick's theorem: There are 2 diagrams for the interaction between a quark and an antiquark: (time runs from left to right!)
If we use **Fierz transformations** (s. Notes!) to rewrite the interaction identically, we can save work and calculate only the first (“direct”) diagram, using the following “effective Lagrangian”:

\[(\mathcal{L}_I + \mathcal{L}_{I,Fierz}) \equiv G_{\pi} \left[ (\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2 \right] + \text{other } q\bar{q} \text{ channels}\]

where \(G_\pi = \frac{2}{9} G\). This is the most familiar form of the NJL model, since it shows the chiral symmetric interactions in the scalar (\(\sigma\)) and pseudoscalar (\(\pi\)) \(q\bar{q}\) channels, which are most important.

An example for other \(q\bar{q}\) channels is the interaction in the vector meson (\(\omega\)) channel:

\[-G_\omega \left( \bar{\psi}\gamma_\mu\psi \right)^2, \text{ where } G_\omega = \frac{1}{9} G.\]

\(U_A(1)\) symmetry breaking is described by another 4-Fermi interaction - the “determinant interaction”. Its effect can be incorporated into a redefinition of the constants \(G_\pi, G_\omega\).
Mean field approximation

Use the **mean field (Hartree) approximation** to define the constituent quark mass $M$ as an effect of the quark self energy: Adding $- (M - m) \bar{\psi}\psi + \text{const}$ and subtracting again, we get:

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\text{res}}$$

where (writing only the scalar and pseudoscalar interaction terms)

$$\begin{align*}
\mathcal{L}_0 &= \bar{\psi} (i \nabla - M) \psi + \text{const} \\
\mathcal{L}_{\text{res}} &= (M - m) \bar{\psi}\psi + G_\pi \left[ (\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5 \vec{\tau}\psi)^2 \right] - \text{const}
\end{align*}$$

Now assume that there is a nonzero expectation value of $\bar{\psi}\psi$ in the vacuum ("quark condensate"):

$$\bar{\psi}\psi = \langle \bar{\psi}\psi \rangle + : \bar{\psi}\psi :$$

where the second term is the normal ordered product. Then determine $M$ and $\text{const}$ by the requirements that $\mathcal{L}_{\text{res}}$ has **no c-number term** and **no linear term** $\propto \bar{\psi}\psi$ (i.e., $\mathcal{L}_{\text{res}}$ is a "true" residual 4-Fermi interaction).
These requirements give

- the gap equation:

\[ M = m - 2G_\pi \langle \bar{\psi}\psi \rangle = m + 2iG_\pi \lim_{\tau \to 0^+} \int \frac{d^4k}{(2\pi)^4} \text{Tr} S_F(k) e^{ik_0\tau} \]

\[ = m + 48i G_\pi M \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - M^2 + i\epsilon} \]

\( (S(k) \) is the Feynman propagator of a quark with mass \( M \).\)

After regularization of the integral, this has to be solved for \( M \).

- the constant term:

\[ \text{const} = - \frac{(M - m)^2}{4G_\pi} \]

We finally get: \( \mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\text{res}} \) with

\[ \mathcal{L}_0 = \bar{\psi} (i \nabla - M) \psi - \frac{(M - m)^2}{4G_\pi} \]

\[ \mathcal{L}_{\text{res}} = G_\pi \left[ \langle \bar{\psi}\psi \rangle^2 + \langle \bar{\psi}i\gamma_5 \tau\psi \rangle^2 \right] + \text{other channels} \]
Spontaneous breaking of chiral symmetry (1)

For the case $m = 0$, the gap equation has 2 solutions: (i) **trivial solution** $M = 0$, (ii) **nontrivial solution** satisfying

$$1 = 48i G_{\pi} \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - M^2 + i\epsilon}$$

Which is the “correct” solution? Compare the vacuum energy densities $\mathcal{E}$ (“effective potentials”) for these 2 cases: From $\mathcal{L}_0$,

$$\mathcal{E}_{\text{vac}}(M) - \mathcal{E}_{\text{vac}}(M = 0) = -12 \int \frac{d^3k}{(2\pi)^3} \left( \sqrt{M^2 + k^2} - k \right) + \frac{M^2}{4G_{\pi}}$$

![Vacuum energy density (\Lambda=0.59 GeV)](image-url)
If $G_\pi$ is larger than some critical value, the energy on the chiral circle $\sigma^2 + \vec{\pi}^2 = M^2 / 4G_\pi^2$ is lower than for $\sigma = \vec{\pi} = 0$. The choice $\vec{\pi} = 0$ in the vacuum corresponds to spontaneous breaking of the chiral symmetry, and the pion becomes a Goldstone boson (which will be verified later).
From $\mathcal{L}_{\text{res}}$, we have the **Feynman rule** for the $q\bar{q}$ interaction in the scalar and pseudoscalar channels (time runs from left to right):

\[
2iG_\pi \left[ (1)_{\gamma \delta} (1)_{\alpha \beta} - (\gamma 5 \vec{\tau})_{\gamma \delta} (\gamma 5 \vec{\tau})_{\alpha \beta} \right]
\]

Then the equation for the $q\bar{q}$ scattering matrix (**Bethe-Salpeter equation**) becomes for fixed total 4-momentum $p^\mu$:

\[
T_{\gamma \delta, \alpha \beta}(p) = K_{\gamma \delta, \alpha \beta} + \int \frac{d^4 k}{(2\pi)^4} K_{\gamma \delta, \epsilon \lambda} S_{\epsilon \epsilon'}(k) S_{\lambda \lambda'}(p + k) T_{\lambda' \epsilon', \alpha \beta}(p)
\]
Inserting the form \( K_{\gamma\delta,\alpha\beta} = C \Gamma_{\gamma\delta} \Gamma_{\alpha\beta} \), where \( C \) is a constant and \( \Gamma \) a matrix, and assuming the solution of the form

\[ T_{\gamma\delta,\alpha\beta}(p) = t(p) \Gamma_{\gamma\delta} \Gamma_{\alpha\beta} \]

we get for the scalar function \( t(p) \) the simple equation:

\[ t(p) = C - iC \Pi(p^2) t(p) \implies t(p) = \frac{C}{1 + iC\Pi(p^2)} \]

with the “bubble graph” (polarization propagator)

\[ \Pi(p^2) \equiv i \int \frac{d^4k}{(2\pi)^4} \text{Tr} \left[ \Gamma S(p + k) \Gamma S(k) \right] \]

\( t(p) \) has a pole at \( p^2 = \mu^2 \) if \( 1 + iC\Pi(\mu^2) = 0 \).

\( \sigma \) channel \( \Rightarrow \Gamma = 1, \ C = 2iG_\pi \); \( \pi \) channel \( \Rightarrow \Gamma = \gamma_5 \tau, \ C = -2iG_\pi \).
Expanding $\Pi(p^2)$ near the pole as $\Pi(p^2) = \Pi(\mu^2) + (p^2 - \mu^2)\Pi'(\mu^2) + \ldots$, we see that near the pole

$$t(p) \rightarrow \frac{ig^2}{p^2 - \mu^2}$$

where $g^2 \equiv (-1/\Pi'(\mu^2))$.

This looks like the exchange of an elementary meson! Therefore, it is natural to interpret $\mu$ as the **meson mass** and $g$ as the **quark-meson coupling constant**.

For the **case of pion** ($\Gamma = \gamma_5 \tau$): By comparing the pion pole condition $1 + 2G_\pi \Pi_\pi(m_\pi^2) = 0$ to the gap equation for $m = 0$ (exact chiral symmetry), it is easy to see that $m_\pi^2 = 0 \Rightarrow \text{Pion is really the Goldstone boson.}$
Definition of electromagnetic current of pion:

\[
\frac{1}{\sqrt{4E_pE_p'}} \int d^4z \ e^{-i\mathbf{q}\cdot\mathbf{z}} \langle \mathbf{p}' | \bar{\psi}(\mathbf{z}) \gamma^\mu \left( \frac{1}{6} + \frac{\tau_3}{2} \right) \psi(\mathbf{z}) | \mathbf{p} \rangle \\
\equiv (2\pi)^4 \delta^{(4)}(\mathbf{p}' - \mathbf{p} - \mathbf{q}) j^\mu(q)
\]

Here we use covariant normalization of states:

\[
\langle \mathbf{p}' | \mathbf{p} \rangle = 2(2\pi)^3 E_p \delta^{(3)}(\mathbf{p}' - \mathbf{p}), \text{ where } E_p = \sqrt{\mathbf{p}^2 + m^2_\pi}.
\]

According to Mandelstam’s theory of bound state matrix elements, the current \( j^\mu(q) \) can be calculated from Feynman diagrams:

The \( \pi^+ \) charge form factor is then defined by

\[
j^\mu(q) = \frac{(p' + p)^\mu}{\sqrt{4E_pE_p'}} F_\pi(Q^2) \quad (Q^2 \equiv -q^2 > 0 \text{ for electron scattering})
\]
Charge form factor of $\pi^+$ (2)

Inserting $\gamma_5 \tau_+ g$ at the left pion-quark vertex and $\gamma_5 \tau_- g$ at the right vertex ($\tau_\pm = (\tau_1 \pm \tau_2)/\sqrt{2}$), we obtain

$$j^\mu(q) = \frac{1}{\sqrt{4E_p E_p'}} 6i g^2 \int \frac{d^4 k}{(2\pi)^4} \text{Tr}_D \left[ \gamma_5 S(p' + k) \gamma^\mu S(p + k) \gamma_5 S(k) \right]$$

This can be evaluated by using one of the regularization schemes (see Notes!).

Check current conservation and charge conservation: By using elementary Ward-like identities

$$q_\mu \left( S(k') \gamma^\mu S(k) \right) = - (S(k') - S(k))$$

$$S(k) \gamma^\mu S(k) = - \frac{\partial S(k)}{\partial k_\mu}$$

we get

$$q_\mu j^\mu = \frac{-g^2}{\sqrt{4E_p E_p'}} g^2 (\Pi_\pi (p'^2) - \Pi_\pi (p^2)) = 0 \quad \text{(because } p'^2 = p^2 = m_\pi^2)$$

$$j^\mu(q = 0) = \frac{-g^2}{2E_p} \left( \frac{\partial \Pi_\pi(p^2)}{\partial p_\mu} \right) = \frac{p^\mu}{E_p} \quad \text{(from definition of } g^2)$$
“bare quarks” (dotted line) refers to the formula on previous slide using the proper-time cut-off, and “monopole” (solid line) is the empirical pion form factor determined from experiment:
\[ F_{\pi,\text{emp}} = \frac{1}{1 + Q^2/(0.5 \text{ GeV}^2)} \].

The following corrections due to intrinsic quark form factors (\( \gamma^\mu \rightarrow \gamma^\mu F_q(Q^2) \)) are also shown:
(i) pion cloud around quarks, and (ii) \( \gamma - \rho \) coupling (cf. Vector Meson Dominance model).
If we set $q = 0$ in the formula for the current, and replace the quark charge operator by the number operator for up quarks $(1 + \tau_3)/2$, we get a "number sum rule" for the up quark:

$$\frac{1}{2E_p} \langle p|\bar{\psi}(0)\gamma^\mu \frac{1 + \tau_3}{2}\psi(0)|p\rangle = N_u \frac{p^\mu}{E_p}$$

where $N_u = 1$ is the number of u-quarks in $\pi^+$. If we define the up-quark correlation function in the pion as

$$M^\mu(p, k) = i \int d^4\omega e^{ik\cdot\omega} \langle p|\bar{\psi}(0)\gamma^\mu \frac{1 + \tau_3}{2}\psi(\omega)|p\rangle$$

we can write the above number sum rule in the form

$$-i \int \frac{d^4k}{(2\pi)^4} M^\mu(p, k) = 2p^\mu N_u$$

where

$$N_u = \frac{1}{2p^\mu} \left( \begin{array}{c} \gamma^\mu \frac{1 + \tau_3}{2} \\ p \\ \gamma^\mu \frac{1 + \tau_3}{2} \\ p \end{array} \right) (\mu \text{ fixed})$$
**Quark momentum distribution in $\pi^+$ (2):**

We see: The operator insertion $\gamma^\mu (1 + \tau_3)/2$ counts the number of u-quarks with all possible momenta $\Rightarrow$ The operator insertion $O_u^\mu \equiv \gamma^\mu (1 + \tau_3)/2 \cdot \delta(x - k^\mu/p^\mu)$ will count the number of u-quarks which have a **fraction** $x$ of the **momentum component** $p^\mu$.

In the description of Deep Inelastic Scattering (DIS), one needs the case $\mu = +$. (Then $k^+ \equiv (k^0 + k^3)/\sqrt{2}$ is the "light-cone plus-component" of $k^\mu$.) We then get for the number of u-quarks with fraction $x$ of the pion momentum component $p^+$:

$$f_{u}^{\pi^+}(x) = \frac{-i}{2p^+} \int \frac{d^4k}{(2\pi)^4} \delta(x - \frac{k^+}{p^+})M^+(p, k)$$

with normalization $\int_0^1 f_{u}^{\pi^+}(x)dx = N_u = 1$.

Note: The 3-axis is defined as the direction of $p$. 

\[\text{Diagram:} \quad f_u(x) = \frac{1}{2p^+} \begin{pmatrix} k_0 & k_3 \\ p & k-p \end{pmatrix} \begin{pmatrix} O_u^+ \\ k \end{pmatrix} \]
The distribution \( f_{u}^{\pi^{+}}(x) \) is obtained from the above Feynman diagram as:

\[
f_{u}^{\pi^{+}}(x) = \frac{ig^{2}}{2p^{+}} \int \frac{d^{4}k}{(2\pi)^{4}} \text{Tr} \left[ \gamma_{5} \tau_{-} S(k) \gamma^{+} \frac{1 + \tau_{3}}{2} S(k) \gamma_{5} \tau_{+} S(k - p) \right] \delta(x - \frac{k^{+}}{p^{+}})
\]

We can perform the \( k_{-} \) integral by residues, expressing the propagator \( S(k) = \frac{k + M}{(k^{2} - M^{2} + i\epsilon)} \) by light-cone variables:

\[
S = \frac{k^{-} \gamma^{+} + k^{+} \gamma^{-} - \mathbf{k}_{\perp} \cdot \gamma_{\perp} + M}{2k^{+}} \left( \frac{\Theta(k^{+})}{k^{-} - e_{k} + i\epsilon} + \frac{\Theta(-k^{+})}{k^{-} - e_{k} - i\epsilon} \right)
\]

where \( e_{k} = (\mathbf{k}_{\perp}^{2} + M^{2})/2k^{+} \) and \( \mathbf{k}_{\perp} = (k_{1}, k_{2}) \). The result is

\[
f_{u}^{\pi^{+}}(x) = 6g^{2} \int \frac{d^{2}k_{\perp}}{(2\pi)^{3}} \frac{k_{\perp}^{2} + M^{2}}{[k_{\perp}^{2} + M^{2} - m_{\pi}^{2}x(1 - x)]^{2}}
\]

In this simple valence quark picture of \( \pi^{+} \) we have \( f_{d}^{\pi^{+}}(x) = f_{u}^{\pi^{+}}(x) \). Experimental information comes from the DIS structure function

\[
F_{2}^{\pi^{+}}(x) = x \left( \sum_{q} e_{q}^{2} f_{q}^{\pi^{+}}(x, Q^{2}) + \sum_{q} e_{q}^{2} f_{\pi}^{\pi^{+}}(x, Q^{2}) \right), \text{ where } q = u, d, \ldots
\]
Results for $u$ distribution in $\pi^+$

- Introduction
- Motivations
- Lagrangian
- Lagrangian
- Mean field approximation
- Gap equation
- Symmetry breaking
- Mesons
- Pion form factor
- Quark distribution in pion
- Evolution
- Comments

- solid line: NJL result on previous slide, using the invariant mass cut-off scheme (see Notes!)

- dashed line: $Q^2$ evolution up to 4 GeV$^2$, assigning a low energy scale $Q_{0}^2 = 0.18$ GeV$^2$ to the solid (NJL) line

- dotted line: empirical distribution at $Q^2 = 4$ GeV$^2$
Notes on the $Q^2$ evolution

- In NJL model, there are no gluons. But in QCD, a quark can give momentum to a gluon, and the gluon to sea quarks, etc.

- Probability of gluon radiation depends on the "resolution scale" ($Q^2$) in DIS: Probed with higher resolution, more quark momentum appears to be carried by gluons.

- This $Q^2$ dependence is calculable in perturbative QCD, if we know $f_q(x)$ at a low resolution scale ($Q^2_0$), where we can assume that we have only quarks. This value $Q^2_0$ defines the energy scale of the NJL model, and is treated as a parameter here.
Comments on the figures

- **Fig.1:** Solid lines: Dyson-Schwinger parametrizations, see: A. Holl et al, Phys. Rev. C 71 (2005), p. 065204; Eqs. (63), (64). The results do not depend much on the parameter $\omega$ if $0.3 < \omega < 0.5$. We show the cases $\omega = 0.4$ (case I) and $\omega = 0.5$ (case II). (For other investigations on the infrared enhancement, see: M.S. Bhagwat et al, Phys. Rev. C 68 (2003), 015203; C.S. Fischer et al, Phys. Rev. D 67 (2003), 094020.) 1-loop perturbation theory (dotted line): $\alpha_s (k) = \frac{4\pi}{\beta_0} \frac{1}{\ln(k^2/\Lambda_{QCD}^2)}$, $\beta_0 = 25/3$, $(N_f = 4)$, $\Lambda_{QCD} = 0.234$ GeV.

- **Fig.2:** Here 3-momentum cut-off is used: $|k| < \Lambda$ with $\Lambda=0.59$ GeV (to reproduce pion decay constant). Chiral symmetry breaking possible for $G_\pi > \pi^2/(6\Lambda^2)$. The case $G_\pi = 6.92$ GeV$^{-2}$ corresponds to quark masses $m = 6.0$ MeV, $M = 400$ MeV.

- **Fig.3:** Here the proper-time cut-off is used: $\Lambda_{UV} = 0.64$ GeV, $\Lambda_{IR} = 0.2$ GeV. The constituent quark mass is $M = 0.4$ GeV. The calculation follows closely that for the nucleon form factors in: T. Horikawa et al, Nucl. Phys. A 762 (2005), p. 102, where the corrections from pion cloud and vector mesons are discussed in detail. Measurements of $F_\pi$ at low $Q^2$ are done by scattering pions off the electrons in liquid hydrogen, and by the reaction $p(e, e'^\pi^+ n)$ (pion electroproduction) at higher $Q^2$ (at JLab), see: V. Tadevosyan et al; Phys. Rev. C75 (2007), p. 055205.

- **Fig.4:** See W. Bentz et al, Nucl. Phys. A 651 (1999), p. 143; Fig. 4. Here the constituent quark mass $M = 0.3$ GeV, and the “invariant mass cut-off” (or “Lepage-Brodsky cut-off”) is used ($\Lambda = 1.47$ GeV in the figure), which is essentially equivalent to the 3-momentum cut-off scheme with $\Lambda = 0.67$ GeV. The computer code for the $Q^2$ evolution is taken from: M. Miyama, S. Kumano, Comp. Phys. Commun. 94 (1996), p. 185. (We use the next-to-leading-order (NLO) evolution with $\Lambda_{QCD} = 0.25$ GeV.)

  The empirical quark distribution in the pion is taken from: P.J. Sutton et al, Phys. Rev. D 45 (1992) 2349. It is extracted from inclusive Drell-Yan pair production: $\pi^\pm N \rightarrow \mu^+ \mu^- X$, which mainly arises from the annihilation of a quark in the nucleon with an antiquark in the pion.

  [For a good introduction to deep inelastic scattering and $Q^2$ evolution, see: R.L. Jaffe, 1985 Los Alamos School on Relativistic Dynamics and Quark Nuclear Physics, ed. M.B. Johnson and A. Pickleseimer (Wiley, new York, 1985).]