SKYRME MODEL LANGUAGE
IN THE THEORY OF NUCLEONS AND NUCLEI

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Abstract

In this talk we try to clarify the problems existing on the way of theorist decided to construct nuclear theory on the generalized Skyrme model background. We conclude that to construct such a model of light nuclei one have to construct a hybrid model where one particle degrees of freedom are concentrated around the surface of the nuclei and soliton with non-trivial structure is located at the center region.

I. INTRODUCTION

In this talk we try to clarify the problems existing on the way of theorist decided to construct nuclear theory on the generalized Skyrme model background. The Lagrangian appropriate for a generalized Skyrme model in the leading classical field approximation

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yields chiral soliton solutions. This solitons are associated with the nucleon or multibaryons and will be used for obtaining spatial structure information on baryons or baryon systems.

The present paper includes discussion of our recent work, extensions, and calculations of the nucleon electromagnetic form factors in the generalized Skyrme model as well. This model involves the theoretical description of the dilaton-quarkonium scalar field and shows its importance in the description of soliton dynamics. We use "dilaton-quarkonium" scalar field to indicate the way we subdivide the gluon condensate in the calculation. This generalized model reproduces the experimental value of the nucleon mass, the input being the experimental value of the pion decay constant and the theoretically derived value of the Skyrme constant, \( e = 2\pi[1] \). The naive, straightforward calculation of the electromagnetic form factors has shortcomings: the values of \( F_\pi \) and \( e \) give too small a nucleon size and the calculated curves do not give the approximate dipole form factor values.

The generalized Skyrme model under consideration follows the formulation of Andrianov et al. \([2]\) This approach uses the framework of the joint chiral and conformal bosonization of the QCD Lagrangian, including chiral and scalar dilaton-quarkonium fields. In such a model the properties of the topological solitons are dramatically changed in numerical value from those in the original Skyrme model. Several authors have introduced an additional scalar field to the Skyrme model for different motivational reasons. For example, Riska and Schwesinger\([3]\) appear to be the first to investigate the isospin independent part of the nucleon-nucleon spin-orbit interaction when a scalar field is added. A number of papers studied the effects a scalar \( \sigma \) meson would have by introducing it as a gluon condensate,\([4],[5],[6]\), and also related, \([2]\) and \([7]\). The purely theoretical and convincing reason is that with the introduction of a scalar field, the conformal anomaly, one of the distinctive features of the QCD Lagrangian, is reproduced. In the SU(2) sector of this Lagrangian, one can construct an effective theory which reproduces the conformal anomaly in the framework of the effective Lagrangian method, introducing a field corresponding to scale invariance. As shown in \([8],[9],[10]\), it leads to the necessary strong attraction at intermediate internucleon distances. In such an approach the starting point is the fermion integral over quark fields, in the low energy regime of QCD. The integral is specified by the finite mode regularization scheme with a cut-off that also plays the role of a low energy boundary. Performing the joint chiral and conformal bosonization on this integral leads to an effective action for chiral \( U(x) \) and dilaton \( \sigma(x) \) fields. This Lagrangian favors the linear sigma model in terms of
the composite field $U(x) \exp(-\sigma(x))$. The resulting effective Lagrangian\cite{2}, generalizing the original Skyrme Lagrangian is

$$L_{eff}(U, \sigma) = \frac{F_{\pi}^2}{4} \exp(-2\sigma)Tr[\partial_{\mu}U\partial^{\mu}U^+] + \frac{N_f F_{\pi}^2}{4}(\partial_{\mu}\sigma)^2 \exp(-2\sigma) +$$

$$+ \frac{1}{128\pi^2}Tr[\partial_{\mu}UU^+, \partial_{\nu}UU^+]^2 - \frac{C_g N_f}{48}(e^{-4\sigma} - 1 + \frac{4}{\varepsilon}(1 - e^{-\varepsilon\sigma}))$$ (1)

where the pion decay constant is taken as the experimental value, $F_{\pi} = 93\text{MeV}$ and $N_f$ is the number of flavors. The gluon condensate, according to QCD sum rules, is $C_g = (300 - 400\text{MeV})^4$\cite{11}. The first two terms are the kinetic terms for the chiral and scalar fields and the third term, the well-known Skyrme term. The effective potential for the scalar field is the result of an extrapolation\cite{2} of the low energy potential to high energies by use of a one-loop-approximation to the Gell-Mann Low QCD $\beta$-function. The parameter $\varepsilon$ is determined by the number of flavors $N_f$ as $\varepsilon = 8N_f/(33 - 2N_f)$.

II. THE NUCLEON

In the baryon sector we choose the chiral field as the spherically symmetric ansatz of Skyrme and Witten, $U(\vec{x}) = \exp[-i\vec{\tau}\vec{n}F(r)]$, where $\vec{n} = \vec{r}/|\vec{r}|$. It is convenient to introduce a new field, $\rho(x) = \exp(-\sigma(x))$. Then, the mass functional in dimensionless variables, $x = eF_{\pi}r$, has the form $M = M_2 + M_4 + V$, where

$$M_2 = 4\pi F_{\pi} e \int_0^{+\infty} dx \left[ \frac{N_f}{4} x^2 (\rho')^2 + \rho^2 \frac{x^2(F')^2}{2} + \sin^2 F \right] ,$$

$$M_4 = 4\pi F_{\pi} e \int_0^{+\infty} dx \left( \frac{\sin^2 F}{2x^2} + (F')^2 \right) \sin^2 F ,$$

$$V = 4\pi F_{\pi}^2 D_{eff} \int_0^{+\infty} dx x^2 [\rho^4 - 1 + \frac{4}{\varepsilon}(1 - \rho^4)] .$$ (4)

In the last equations, the same Skyrme parameter value, $\varepsilon = 2\pi$, is used. The contribution of the potential to the mass is determined by the factor $D_{eff} = C_g N_f/48e^2F_{\pi}^4$. The mass functional leads to a system of equations for the profile functions $F(x)$ and $\rho(x)$, where a prime is used to denote the derivative with respect to $x$,

$$F''[\rho^2 x^2 + 2\sin^2 F] + 2F'x[rho' + \rho^2] + (F')^2 \cdot \sin(2F) -$$
\[-\rho^2 \cdot \sin(2F) - \sin(2F) \cdot \sin^2 F \cdot x^2 = 0, \tag{5}\]

\[\frac{N_f}{2} x [\rho'' + 2 \rho'] - 2 \rho \left[ \frac{x^2 (F')}^2}{2} + \sin^2 F \right] - 4D_{\text{eff}} \cdot [\rho^3 - \rho^{\varepsilon-1}] x^2 = 0, \tag{6}\]

At small distances, \(F = \pi N - \alpha x\) and \(\rho = \rho(0) + \beta x^2\), with \(\rho(0) \neq 0\). For large \(x\), these functions behave as \(F(x) \sim a/x^2\), and \(\rho(x) \sim 1 - b/x^6 + \ldots\).

![FIG. 1: Chiral angle \(F(x)\) in GSM and OSM for \(C_g = (300 \text{ Mev})^4\) and \(N_f = 2\).](image)

According to the virial theorem, the contributions of the individual terms of the mass functional to the energy of the system must obey the condition,

\[M_4 - M_2 - 3V = 0, \tag{7}\]

which can be used to control the accuracy of the numerical solution of the system. There are nontrivial equations between the numbers \(\alpha\) and \(\beta\), \(a\) and \(b\),

\[b = \frac{1}{2} a^2 / D_{\text{eff}}, \tag{8}\]

\[\beta = \left[ \rho(0) \alpha^2 + \frac{4}{3} \left( \rho^3(0) - 1 \right) D_{\text{eff}} \right] / N_f. \tag{9}\]

The choice of boundary conditions ensures a finiteness of the mass functional for a given value of the topological charge \(B = N\). Performing canonical quantization of the rotational
FIG. 2: Scalar meson shape function $\rho(x)$ for $G = C_g^{1/4} = 50\text{ MeV, 350 MeV and 1 GeV}$. 

FIG. 3: Mass spectra of the ground and excited states in GSM (solid line) and OSM (dashed line).

degrees of freedom with the collective variable method, one obtains for the nucleon mass,

$$M_B = M + S(S + 1)/(2I),$$

where the moment of inertia is

$$I = \frac{8\pi}{3}(F_\pi e)^{-3} \int_0^\infty dx \sin^2[\rho^2 x^2 + (F')^2 x^2 + \sin^2 F].$$

Some numerical results are presented in Table 1, where the soliton mean square radius of the corresponding baryon $<r_S^2>$ density distribution is given

$$<r_B^2>^{1/2} = \frac{1}{F_\pi e} \left\{ \frac{2}{\pi} \int_0^\infty dxx^2 F' \sin^2 F \right\}^{1/2}.$$
TABLE I: Static properties ($N_f = 2$) in the generalized Skyrme model with $F_\pi = 93 MeV$, $e = 2\pi$, $C_g = (300 MeV)^4$.

| Present work |
|--------------|
| $M$          | $839 MeV$ |
| $< r^2 >_p$  | $0.67 Fm^2$ |
| $< r^2 >_n$  | $-0.14 Fm^2$ |
| $M_B$        | $1026 MeV$ |

A discussion of partial restoration of chiral symmetry in this model is given in Ref. [1]. The restoration appears as a large deviation of $\rho(0)$ from its asymptotic value of $\rho(0) = 1$. The dependence of the mass spectra on the gluon condensate in the generalized Skyrme model was also discussed in [1].

III. FORM FACTORS OF CHARGE DISTRIBUTIONS

The nucleon electric and magnetic form factors, $G_E(q^2)$ and $G_M(q^2)$ can be calculated from the electromagnetic currents, in the Breit frame where the photon does not transfer energy.

\[
\langle N_f (\frac{\vec{q}}{2}) | \hat{J}_0(0) | N_i (-\frac{\vec{q}}{2}) \rangle = G_E(\vec{q}^2) \xi_f^+ \xi_i ,
\]

\[
\langle N_f (\frac{\vec{q}}{2}) | \hat{J}(0) | N_i (-\frac{\vec{q}}{2}) \rangle = G_M(\vec{q}^2) \xi_f^+ i \vec{\sigma} \otimes \vec{q} \xi_i .
\]

Here, $|N(\vec{p})>$ is the nucleon state with momentum $\vec{p}$, $\xi_i$, $\xi_f$ and two component Pauli spinors, and $\vec{q} \equiv$ momentum transfer.

The isoscalar (S) and isovector (V) nucleon form factors are related to those for the proton and neutron by

\[G_{E,M}^{p,n} = G_{E,M}^S \pm G_{E,M}^V \]   \hspace{0.5cm} (14)

These form factors are normalized to the respective charge and magnetic moments by

\[G_E^p(0) = 1 \quad G_E^n(0) = 0 \]

\[G_M^p(0) \equiv \mu_p = 2.79 \quad G_M^n = \mu_n = -1.91 . \]   \hspace{0.5cm} (15)
We remaked above on the smallness of the nucleon size as determined by the baryon charge density distribution in the model with a dilaton-quarkonium field.

Vector meson dominance means that the isoscalar photon sees $\omega$ meson structure, but not the isoscalar baryon density $\mathcal{B}_0(r)$.

According to vector meson dominance, the isoscalar current is proportional to the $\omega_\mu$-field,

$$ J^\mu_{I=0} = -\frac{m_\omega^2}{3g} \omega_\mu(r) $$  \hspace{1cm} (16) 

and the corresponding charge form factor,

$$ G^S_E(q^2) = -\frac{m_\omega^2}{3g} \int d^3r \exp i\vec{q}\vec{r} \omega(r) . $$  \hspace{1cm} (17) 

The static $\omega(r)$ obeys the equation,

$$ (\nabla^2 - m_\omega^2)\omega(r) = \frac{3g}{2} B(r) = -\frac{3gF'(r)}{4\pi r^2} \sin^2 F(r) . $$  \hspace{1cm} (18) 

From this equation, we obtain,

$$ G^S_E(q^2) = -\frac{1}{2} \frac{m_\omega^2}{m_\omega^2 + q^2} F_V(q^2) , $$  \hspace{1cm} (19) 

Therefore, the effective isoscalar nucleon density is equal baryon charge density $\mathcal{B}_0(r)$ times the $\omega$-meson propagator.

The isovector electromagnetic formfactor has analogous structure,

$$ G^V_E(q^2) = -\frac{1}{2} \frac{m_\rho^2}{m_\rho^2 + q^2} F_V(q^2) , $$  \hspace{1cm} (20) 

In writing the propagators separately, as a factor multiplied into $F^V_E$, $\omega$ and $\rho$, themselves have no substructure or internal dynamics; the corresponding Skyrmion densities are considered as the sources of these $\omega$ and $\rho$ fields. Explicit considerations of the role of vector mesons in the electromagnetic form factors in the $\sigma$ model has been given by Holzwarth[14] and quantum corrections to the relevant baryon properties in the chiral soliton models has been calculated.[15]

The results of the present calculations are given in Figures 4 to 7. The isoscalar part of the Skyrmion electric charge coincides with the baryon density distribution, and for the isovector density from the Skyrmion model one obtains,

$$ \rho^V(x) = \sin^2 F(x) \left[ x^2 \rho^2(x) + (F'(x))^2 x^2 + \sin^2 F(x) \right] . $$  \hspace{1cm} (21)
To take chiral symmetry breaking into account, we must add the pion mass term,
\begin{equation}
\mathcal{L}_\pi = \frac{1}{4} m^2 \pi F^2 \pi e^{-3\sigma} \text{Tr} \left[ U + U^+ \right] - \left( \frac{3}{2} e^{-\sigma} \right),
\end{equation}
to our Skyrme model Lagrangian. The theoretical predictions for the proton electric, neutron electric, proton magnetic and neutron magnetic form factors, compared with data are shown in Figures 4, 5, 6 and 7 respectively. Corresponding values of the proton and neutron mean square radius of the electric charge distribution are 0.78 $Fm^2$ and - 0.19 $Fm^2$.

We have presented our calculations on the nucleon electromagnetic form factors in the framework of the generalized Skyrme model with dilaton quarkonium field. The first calculation in such a model yielded large deviations of the calculated form factors from the dipole approximation formula. We would like to point out here that we use the empirical value of the pion decay constant and the theoretical value for the Skyrme term constant in the vector meson dominance approach to obtain a good description of the form factor data in the finite range of momentum transfer in the measurements. The vector mesons are included only as elements of the hadron substructure of the photon and are not consid-
FIG. 5: Neutron electric form factor as a function of $q^2$ in GeV$^2$ calculated for $F_\pi = 93$, $e = 2\pi$, $N_f = 2$, $C_g = (300\,\text{MeV})^4$, and $m_\pi = 139$. The experimental data shown come from Ref.[16].

Considered as components of the structure in the soliton self-dynamics. Implicit in the approach, though not explicitly proposed, is the possibility of having the role of vector mesons given by higher derivative terms in the effective Lagrangian for soliton dynamics [17]. For example, keeping terms to four orders in the expansion of the effective Lagrangian would lead to a $\rho$ meson-like term and the sixth order terms would give $\omega$-like terms which are important in the calculations of the form factors at the larger momentum transfers.

Lagrangian including $\omega$-field becomes

$$\mathcal{L} = \mathcal{L}_\text{eff}(U, \sigma) - V_\sigma - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \frac{1}{2} e^{2\sigma} m_\omega^2 \omega_\mu \omega^\mu - g_\omega \omega_\mu B^\mu$$

(23)

Here

$$G_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$$

(24)

To discuss skyrmion properties in nuclear interior one can use the ansatz for the scalar and vector fields

$$U(r) = \exp[i \tau \cdot \hat{r} F(r)],$$
FIG. 6: Proton magnetic form factor as a function of $q^2$ in GeV$^2$ calculated for $F_\pi = 93$, $e = 2\pi$, $N_f = 2$, $C_g = (300\,MeV)^4$, and $m_\pi = 139$. The experimental data shown come from Ref.\[16\].

$$G_p(q^2)/G_p(0)$$

where $R$ measures the distance from the center of the nucleus at rest, and $r$ is the coordinate from the center of the skyrmion.

To introduce the mean field -like approximation to for the meson fields one can use

$$\sigma_B = \sigma_0 + \delta \sigma_1 + \delta \sigma_2 + \cdots + \delta \sigma_N,$$

$$\omega_B = \omega_0 + \delta \omega_1 + \delta \omega_2 + \cdots + \delta \omega_N,$$

where $\sigma_0, \omega_0$ are the mean field constant values of the scalar and the $\omega$ and $\delta \sigma, \delta \omega$ represent the fluctuations.

The topological baryon density

$$B^\mu = \frac{\epsilon^{\mu\alpha\beta\gamma}}{24\pi^2} \text{tr} \left[(U^\dagger \partial_\alpha U) \left(U^\dagger \partial_\beta U\right) \left(U^\dagger \partial_\gamma U\right)\right],$$

(28)
FIG. 7: Neutron magnetic form factor as a function of $q^2$ in $\text{GeV}^2$ calculated for $F_\pi = 93$, $e = 2\pi$, $N_f = 2$, $C_g = (300 \text{MeV})^4$, and $m_\pi = 139$. The experimental data shown come from Ref. [16].

with the the product ansatz will give us

$$B_0 = b_1 + b_2 + \cdots + b_N,$$

$$\text{(29)}$$

Skyrmion mass becomes depending on position R:

$$M(R) = 4\pi \int_0^\infty r^2 dr M(r)$$

$$M(r) = e^{2\sigma} \frac{F_\pi^2}{8} \left[ (F')^2 + 2 \frac{\sin^2 F}{r^2} \right] + \frac{1}{2e^2} \frac{\sin^2 F}{r^2} \left[ \sin^2 F + 2(F')^2 \right]$$

$$\text{(30)}$$

A key element of the nucleon interaction in the nucleus is the spin-orbit potential if we want to construct shell model-like theory. There is very important source of spin-orbit interaction[18]

$$W_{s.o.} = -\frac{\mathbf{S} \cdot \mathbf{L}}{2M_0 \lambda(R)} \omega_1(R).$$

$$\text{(31)}$$

It is due to the transformation of the fields to a rotating frame, essentially the coupling of the baryon current to the $\omega$ field in a rotating nucleus analogous to the isoscalar coupling to the photon[18].
In the Dirac type of Walecka models [19], the spin-orbit interaction arises from the coupling of the lower components of the Dirac wave function. Here, it arises from the interaction of the rigid rotation of the nucleon with the flow of the mean fields, which is quite a different mechanism.

So one could decide that we are on the way to construct nuclear shell model on Skyrme model background. But using the same arguments and R-dependence of sigma-field we can obtain that the nucleon swells inside the nucleus to almost twice its free size[18]. This is a big trouble in our exercises. The nucleons no longer act as free enteties and the solitons overlap.

It is the only way to avoid the problem - to consider the interior of nuclei as one soliton with complicated structure. Let consider original Skyrme model [21] without dilaton and omega-fields

Here we follow the paper [22] (see also [23]). For a variational treatment we use the chiral field $U$

$$U(\vec{r}) = \cos F(r) + i(\vec{r} \cdot \vec{N}) \sin F(r). \quad (32)$$

with the following assumption about the configuration of the isotopic vector field $\vec{N}$:

$$\vec{N} = \{ \cos(\Phi(\phi, \theta)) \sin(T(\theta)), \sin(\Phi(\phi, \theta))\sin(T(\theta)), \cos(T(\theta)) \}. \quad (33)$$

Here $\Phi(\phi, \theta)$, $T(\theta)$ are some arbitrary functions of angles $(\theta, \phi)$ of the vector $\vec{r}$ in the spherical coordinate system.

Let us consider the Lagrangian density $\mathcal{L}$ for the stationary solution:

$$\mathcal{L} = \frac{F^2 \pi}{16} \text{Tr}(L_\mu L^\mu) + \frac{1}{32e^2} \text{Tr}[L_\mu, L_\nu]^2. \quad (34)$$

Here $L_\mu = U^+ \partial_\mu U$ are the left currents.

Variation of the functional $L = \int \mathcal{L} d\vec{r}$ with respect to $\Phi$ leads to an equation which has a solution of the type

$$\Phi(\theta, \phi) = k(\theta)\phi + c(\theta) \quad (35)$$

with a constraint

$$\frac{\partial}{\partial \theta} \left[ \sin^2 T(\theta) \sin \theta \frac{\partial \Phi(\theta, \phi)}{\partial \theta} \right] = 0. \quad (36)$$

It is easily seen from eq. (36) (see also [22]) that functions $k(\theta)$ and $c(\theta)$ may be piecewise constant functions.
FIG. 8: Dependence of the classical masses $M$ in dimensionless variables $\pi \frac{F_{i}}{e}$ on the baryon charge $B$.

Moreover, $k^{(m)}$ must be integer in any region $\theta_{m} \leq \theta \leq \theta_{m+1}$, where $\theta_{m}$, $\theta_{m+1}$ are successive points of discontinuity of $\partial \Phi_{i}(\theta, \phi)/\partial \theta$. The positions of these are the points determined by the condition

$$T(\theta_{m}) = m\pi , \quad T(\pi) = n\pi$$

with integer $m$, as follows from Eq.(36).

The soliton mass is given by a functional which can be represented as a sum of contributions from different $\theta$ - regions. The functions $F(x)$ and $T(\theta)$ have to obey the equations derived in [22], in each $\theta$ - region with given number $k^{(m)}$.

We obtain an almost linear dependence of the classical masses $M$ on the baryon charge $B$. The results of the calculations are given in Figure 8.

IV. CONCLUSIONS

The one particle ($B=1$) degrees of freedom are concentrated around the surface of the nuclei and the soliton with non-trivial structure ($B > 1$) is located at the center region.

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