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LA-UR -84-823

CONF-8403101--6

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LA-UR--84-823

DE84 010062

TITLE: HIGH ENERGY NUCLEAR STRUCTURES

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SUBMITTED TO: to be presented at the Nuclear Dynamics Workshop III to be held at Copper Mountain, CO, on March 4-9, 1984

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HIGH ENERGY NUCLEAR STRUCTURES

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In conventional nuclear physics the nucleus is described as a non-relativistic many-body system, which is governed by the Schrödinger equation. Nucleons interact in this framework via static two-body potentials, mesonic degrees of freedom are neglected. However, although this conventional approach has usually been very successful, the validity of its basic assumptions is questionable[1,2].

An alternative description of nuclear physics in terms of a relativistic field theory has been developed by Walecka [1]. The model Lagrangian containing baryons, σ-mesons and ω-mesons was subsequently extended to include also $\vec{\pi}$-mesons and ρ-mesons [3,4]. An essential feature of such a nuclear Lagrangian is its renormalizability.

Nuclear field theory has been applied to study nuclear matter as well as finite nuclei. Within the mean field approximation the known bulk properties of nuclei such as binding energy, density, and compressibility are well reproduced. Charge and matter distributions of closed shell nuclei are in good agreement with experimental results, so are rms radii and single-particle energy levels [4].

In addition to the description of known nuclear structure the field theoretical approach may reveal entirely new nuclear phenomena, based on the explicit treatment of mesonic degrees of freedom. The existence of such abnormal nuclear states was proposed by Lee and Wick employing the σ-model Lagrangian [5]. There the non-linearity of the meson field equations allows for soliton solutions in the presence of nucleons, in particular the σ-field may exhibit a kink.

Different types of soliton solutions occur in gauge theories with hidden symmetries. In the phenomenological Lagrangian [3] the ρ-meson is described by a non-abelian gauge field, that acquires its mass spontaneously due to the non-vanishing vacuum expectation value of a Higgs field. A general ansatz for soliton solutions of such a gauge theory was given by Dashen et al. [6]. A specific solution and its possible implications for nuclear physics like anomalous nuclear states were discussed by Boguta [7].

In the following we address the question whether anomalous nuclear structures do occur in the full phenomenological Lagrangian [8]

$$\begin{aligned} \mathcal{L} = & - \frac{1}{4} \hat{F}_{\mu\nu} \cdot \hat{F}_{\mu\nu} - \bar{\psi} \gamma_{\mu} \left(\frac{\partial}{\partial x_{\mu}} - i g_{\rho} \frac{\hat{\tau}}{2} \cdot \hat{\rho}_{\mu}\right)\psi - g_s \bar{\psi}(\sigma + i \gamma_5 \hat{\tau} \cdot \hat{\pi})\psi \\ & - \frac{1}{2} \left(\frac{\partial \sigma}{\partial x_{\mu}}\right)^2 - \frac{1}{2} \left(\frac{\partial \hat{\pi}}{\partial x_{\mu}} + g_{\rho} \hat{\rho}_{\mu} \times \hat{\pi}\right)^2 - \frac{1}{2} \left|\left(\frac{\partial}{\partial x_{\mu}} - i g_{\rho} \frac{\hat{\tau}}{2} \cdot \hat{\rho}_{\mu}\right) H\right|^2 \\ & - \lambda_H/4 \, (H^+ H - V^2)^2 - \lambda_c/4 \, (\sigma^2 + \hat{\pi}^2 - \sigma_0^2)^2 \quad . \end{aligned} \tag{1}$$

Here ψ represents the nucleon field, that couples to the ρ-field through the covariant derivative and to the σ- and π-field. Note that no explicit mass term for the nucleon occurs, its mass is given by the non-vanishing expectation value of the σ-field

$$m_N = g_s \langle\sigma\rangle = g_s \, \sigma_0 \quad .$$

The field strength of the ρ-meson is denoted by $\hat{F}_{\mu\nu}$. The hat symbolizes an isovector. $\hat{\tau}$ represents the usual Pauli matrices acting in isospin space. The ρ-field mass is given by

$$m_{\rho} = \frac{1}{2} g_{\rho} V \quad ,$$

where V is the non-vanishing component of the expectation value of the Higgs field H.

The Lagrangian (1) joins the linear σ-model with a gauge field theory with hidden symmetry. Finite energy soliton solutions to both parts separately have been studied [6,7,9]. We therefore combine the ansatz for the gauge field

$$\rho_c^a \propto \varepsilon_{abc} \, x^b$$

and the Higgs field [6]

$$H \propto \hat{t} \cdot \underset{\sim}{r} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

with the hedgehog ansatz for the pion field [9]

$$\hat{\pi} \propto \underset{\sim}{r} \quad .$$

The Euler-Lagrange equations derived from Lagrangian (1) then reduce to a set of non-linear coupled differential equations, depending only on the radial variable. The nucleon wavefunction possesses the conserved quantum number k ($\underset{\sim}{k} = \underset{\sim}{l} + \underset{\sim}{s} + \hat{t}/2$).

A remarkable feature of the above Lagrangian is that it leads to a conserved topological quantum number of the Skyrme type. It can be constructed from the quaternion

$$U = \sigma + i\, \hat{t} \cdot \hat{\pi} \quad ,$$

when the σ- and π-fields are normalized to satisfy $U^{+}U = 1$ [8].

Let us now turn to the physical properties of soliton solutions obtained with the above ansatz. First we have to address the question of stability of such solitons. The existence of a conserved topological quantum number alone does not assure stability of the solution. The topological structure of the σ- and π-field may remain unaffected by a change in the structure of the ρ- and Higgs fields [6], that is consistent with the hedgehog ansatz. We suppose, however, that the presence of nucleons renders the solution stable.

We estimate the excitation energy of such states to be of the order of several hundred MeV. The rho soliton contributes about 1.5 GeV. Considerable energy is regained, however, due to the strong binding of nucleons by the σ- and π-field. An exact numerical computation of the excitation energy is in progress.

The possible anomalous nuclei are limited to states with small electric charge and baryon number. This is due to the fact that we obtain self-consistent solutions to the equations only for nucleons in k = 0 states, corresponding to the $s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}$ states of the Dirac equation. Thus to increase the number of nucleons present, states with k = 0 higher in energy have to be occupied. Clearly only a limited number of such states will be bound.

Finally, we note that the usual short-range hadronic interaction undergoes a metamorphosis in the soliton solution and becomes long-ranged [7,8]. Consequently, such an anomalous nuclear state will exhibit a huge reaction cross section. Anomalous nuclei with large lifetimes and cross sections have been observed experimentally [10].

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