Quantum Nucleardynamics as an $SU(2)_N \times U(1)_Z$ Gauge Theory

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It is shown that quantum nucleardynamics (QND) as an $SU(2)_N \times U(1)_Z$ gauge theory, which is generated from quantum chromodynamics (QCD) as an $SU(3)_C$ gauge theory through dynamical spontaneous symmetry breaking, successfully describes nuclear phenomena at low energies. The proton and neutron assigned as a strong isospin doublet are identified as a colorspin plus weak isospin doublet. Massive gluon mediates strong interactions with the effective coupling constant $G_G/\sqrt{2} = g^2_0/8M^2_G \approx 10$ GeV$^{-2}$ just like Fermi weak constant $G_F/\sqrt{2} = g^2_0/8M^2_W \approx 10^{-5}$ GeV$^{-2}$ in the Glashow-Weinberg-Salam model where $g_n$ and $g_w$ are the coupling constants and $M_G$ and $M_W$ are the gauge boson masses. Explicit evidences such as lifetimes and cross sections of nuclear scattering and reaction, nuclear matter and charge densities, nucleon-nucleon scattering, magnetic dipole moment, gamma decay, etc. are shown in support of QND. The baryon number conservation is the consequence of the $U(1)_Z$ gauge theory and the proton number conservation is the consequence of the $U(1)_f$ gauge theory.

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There are, in the one hand, two distinct problems in quantum chromodynamics (QCD) [1] with quarks and gluons as fundamental constituents. One is the confinement, which is not rigorously explained in the low energy region, and the other is the Θ vacuum [2], which is a superposition of the various false vacua, violating CP symmetry. At lower energies, on the other hand, many nuclear effective models as the alternatives of QCD were proposed but their applications are not complete and limited to a few aspects. It is thus the motivation of quantum nucleardynamics (QND), which is derived from QCD as the consequence of the confinement and Θ vacuum, to explain diverse nuclear phenomena at lower energies consistently. For examples, nuclear issues to be clarified are as follows: Lande’s spin g-factor for nucleon, constant nucleon density, intrinsic quantum number, nucleon-nucleon scattering data, baryon number conservation, proton number conservation, etc. These phenomena at relatively lower energies may be partly explained by nuclear effective models but each effective model is only applicable to limited issues. In this context, it is proposed that QND as an $SU(2)_N \times U(1)_Z$ gauge theory [3] is the theory for strong interactions of nucleons just as the Glashow-Weinberg-Salam (GWS) model [3] as an $SU(2)_L \times U(1)_Y$ gauge theory is the theory for electroweak interactions of quarks and leptons.

QND is generated from QCD through dynamical spontaneous symmetry breaking (DSSB) mechanism, whose details are explained in reference [3]: $SU(3)_C \rightarrow SU(2)_N \times U(1)_Z \rightarrow U(1)_f$. The Lagrangian density [3] of QND as an $SU(2)_N \times U(1)_Z$ gauge theory has the similar form with QCD as an $SU(3)_C$ gauge theory without the explicit mass term:

$$\mathcal{L}_{QND} = -\frac{1}{2}TrG_{\mu\nu}G^{\mu\nu} + \sum_{i=1}^{2} \bar{\psi}_i \gamma^\mu D_\mu \psi_i + \Theta \frac{g^2_n}{16\pi^2} TrG_{\mu\nu} \tilde{G}^{\mu\nu}$$

(1)

where the bare Θ term [2] is a nonperturbative term added to the perturbative Lagrangian density with an $SU(2)_N \times U(1)_Z$ gauge theory. The subscript $i$ stands for the classes of pointlike spinor $\psi_i$ and $A_\mu = \sum_{a=0} A^a_\mu \lambda^a / 2$ stand for gauge fields. The field strength tensor is given by $G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig_{n}[A_\mu,A_\nu]$. $G^\mu\nu$ is the dual field strength tensor. The Θ term apparently odd under both P, T, C, and CP operation. The proton and neutron as spinors possess up and down color-spins as a doublet just like up and down strong isospins:

$$\left( \begin{array}{c} 1 \\ \downarrow \end{array} \right) \uparrow c, \quad \left( \begin{array}{c} 0 \\ 1 \end{array} \right) \downarrow c$$

(2)

This implies that conventional, global $SU(2)$ strong isospin symmetry introduced by Heisenberg [3] is postulated as the combination of local $SU(2)$ colorspin and local $SU(2)$ weak isospin symmetries. The overall wave function for a nucleon may thus be expressed by $\psi_N = \psi(\text{colorspin})\psi(\text{isospin})\psi(\text{spin})\psi(\text{space})$. There exist two types of nucleons, one of which is the color doublet, which is governed by QND, and the other of which is color singlet just as there are two type of quarks and leptons, weak isospin doublet and singlet, in the GWS model: this concept is not contradicted with the conventional concept for hadrons as color singlet. In this scheme, gluon is a massive gauge boson rather than a massless gauge boson. The new concepts of nucleons as color doublets and massive gauge bosons are required to explain the confinement of quarks, the Θ vacuum, and the violation of discrete symmetries. The Yukawa potential due to massive gluon confines quarks and gluons. Discrete symmetries are non-pertubatively broken by the Θ vacuum as illustrated in the spectra of baryons: the CP and T violation of the neutron electric dipole moment with $\Theta \leq 10^{-9}$ [4], the CP violation of the baryon asymmetry $\delta_B \approx 10^{-10}$ [4], the P violation of no parity partners in baryons and mesons, etc. It is also confirmed that nucleons conserve
the vector current but do not conserve the axial vector current just as quarks and leptons conserve the (V - A) current but do not conserve the (V + A) current. The nuclear coupling constant $g_n^2 = c_f g^2 = \sin^2 \theta_R g^2 = g^2/4$ is given in terms of the strong coupling constant $g$ and the color factor $c_f$. The effective strong coupling constant $G_R/\sqrt{2} = g_R^2/8M_G^2 \approx 10$ GeV$^{-2}$ like Fermi weak constant $G_F/\sqrt{2} = g_w^2/8M_G^2 \approx 10^{-5}$ GeV$^{-2}$ and the color mixing angle $\sin^2 \theta_R = 1/4$ like the Weinberg mixing angle $\sin^2 \theta_W = 1/4$ thus play important roles in nuclear interactions [3]. In the following, it is briefly shown how QND is applied to strong nuclear interactions at both low and high energies: the details of QND and its applications including nucleon mass generation are discussed in two references [3,4].

There are several, explicit examples of lifetimes and cross sections, supporting QND as an $SU(2)_N \times U(1)_Z$ gauge theory in analogy with the GWS model as an $SU(2)_L \times U(1)_Y$ gauge theory. The state $\Sigma^0$ is formed as a resonance of central mass 1385 MeV in a $K^+p$ interaction: $K^- + p \rightarrow \Sigma^0 \rightarrow \Lambda + \pi^0$ where the Q-value in the decay 130 MeV and the lifetime $\tau = 1/\Gamma \approx 10^{-23}$ s are estimated from the measured decay width $\Gamma = 36$ MeV. If the decay rate $\Gamma \approx C_{G_R}^2 m_{\Sigma}^2 \approx \sin^2 \theta_R$ is used in analogy with the muon decay rate $\Gamma = G_F^2 m_{\mu}^2/192\pi^3$ of weak interactions, the $\Sigma^0$-hyperon lifetime becomes the order of $10^{-23}$ s compared with the muon lifetime in the order of $10^{-6}$ s. In the strong decay process, the exchange of massive gluon is taken into account like the exchange of massive intermediate vector boson in the weak decay process. The strong decay $\Delta \rightarrow n + p$ and the weak decay $\Sigma^0 \rightarrow n + \pi^+$ have almost same 0.12 GeV kinetic energy, approximately. Their lifetime ratio becomes

$$\frac{\tau(\Delta \rightarrow n + p)}{\tau(\Sigma \rightarrow n + \pi^+)} \approx \frac{1/C_{G_R}^2 m_{\Sigma}^2}{1/C_{G_F}^2 m_{\Sigma}^2} \approx 10^{-23} \text{ s}. \quad (3)$$

Similarly, the lifetime ratio between $\Sigma^0 \rightarrow \Lambda + \pi^0$ and $\Sigma^- \rightarrow n + \pi^-$ is found to be

$$\frac{\tau(\Sigma^0 \rightarrow \Lambda + \pi^0)}{\tau(\Sigma^- \rightarrow n + \pi^-)} \approx \frac{1/C_{G_R}^2 m_{\Sigma}^2}{1/C_{G_F}^2 m_{\Sigma}^2} \approx 10^{-23} \text{ s}. \quad (4)$$

Since the typical cross section in weak interactions can be estimated by $\sigma \approx C_{G_R}^2 T^2 \approx 10^{-44} \text{ m}^2$, the typical cross section in strong interactions is $\sigma \approx C_{G_R}^2 T^2 \approx 10^{-30} \text{ m}^2$, which gives good agreement with experiment result. In the decay of $\Delta^{++}$, which hints the color quantum number, $\Delta^{++} \rightarrow \pi^+ p$, the lifetime of $\Delta^{++}$ is $10^{-23}$ s. This can be interpreted by the distance of about 1 fm estimated by the gluon mass of about 300 MeV in this scheme. In the strong interaction of $\pi + p \rightarrow \pi + p$ and weak interactions of $\nu + p \rightarrow \nu + p$, the cross section ratio around the kinetic energy $T = 1$ GeV becomes

$$\frac{\sigma(\pi + p \rightarrow \pi + p)}{\sigma(\nu + p \rightarrow \nu + p)} \approx \frac{C_{G_R}^2 T^2}{C_{G_F}^2 T^2} \approx 10^{-11} \text{ mb}. \quad (5)$$

These examples described above explicitly exhibit the typical lifetimes and cross sections in strong interactions as expected.

The color $SU(3)_C$ symmetry generates the $SU(2)_N \times U(1)_Z$ symmetry, which governs nuclear strong dynam-ics, and the $U(1)_f$ symmetry, which governs nuclear electromagnetic dynamics, with the condensation of singlet gluons. The $SU(2)_2 \times U(1)_Z$ symmetry and $U(1)_f$ symmetry using the symmetric color factors, $c_{f_i} = (c_f, c_{f_2}, c_{f_3}, c_{f_4}) = (1, 1/3, 1/4, 1/12, 1/16)$, are applied to the typical strong interactions $[3]$. The color factors are related to the strong color mixing angle $\sin^2 \theta_R$ just like the isospin factors are related to the Weinberg mixing angle $\sin^2 \theta_W$: for example, $c_{f_2} = \sin^2 \theta_R = 1/4$ and $c_{f_2} = \sin^2 \theta_W = 1/4$. The factors described above are the pure color factors due to color charges but the effective color factors used in nuclear dynamics must be multiplied by the isospin factor $c_{f_2} = \sin^2 \theta_W = 1/4$ with the weak Weinberg angle $\sin \theta_W$. Since the proton and neutron are an isospin doublet as well as a color doublet:

$$c_{f_2}^2 = \frac{1}{12} \frac{1}{16} \frac{1}{48} \frac{1}{64} (1/12, 1/16, 1/48, 1/64)$$

for symmetric configurations. For example, the electromagnetic color factor for the $U(1)_f$ gauge theory becomes $c_{f_2}^2 = \alpha_s/64 \approx 1/137$ when $\alpha_s = 0.48$ at the QCD scale $[3]$. The coupling constant $\alpha_f = \alpha_s/16$ for a $U(1)_f$ gauge theory at the strong scale is used to evaluate excitation levels. The pure color coupling constant $\alpha_f = \alpha_s/16 = \alpha_w/4$ has about four times stronger than the coupling constant $\alpha_w = \alpha_w/4$ for a $U(1)_w$ gauge theory at the weak scale: the effective coupling constant $\alpha_f^2 = \alpha_f^2 \alpha_f = \alpha_s/64 = \alpha_w$. The emission of energetic photons as gamma radiation is typical for a nucleus deexcitation from some high lying excited state to the ground state configuration. This represents a reordering of the nucleon in the nucleus with a lowering of mass from the excited mass to the lowest mass. Electromagnetic transition due to the proton charge and gamma decay are well established subjects. For another example, nuclei with closed shell plus one valence nucleon is considered in analogy with the hydrogen atom. The Coulomb potential originated from color charges is thus automatically realized in nucleon-nucleon electromagnetic interactions in terms of the $U(1)_f$ gauge theory in addition to the Coulomb potential originated from isospin electric charges. The separation energy of a valence nucleon is $m_n \alpha_f^2/2 \approx 0.42 \text{ MeV}$ with the coupling constant $\alpha_f \approx 0.03$.

The conservation of the proton number is the result of the $U(1)_f$ local gauge theory just as the conservation of the electron number is the result of the $U(1)_e$ local gauge theory. The charge quantization is given by $Q_f = C_3 + Z_3/2$ where $C_3$ is the third component of the color-spin operator $C$ and $Z_3$ is the hyper-color charge operator $[3]$. This form has the analogy with the electric charge quantization $Q_e = T_3^w + Y^w/2$ in the GWS model and $\tilde{Q}_e = T_3^w + Y^w/2$ in the quark model. The hyper-color charge operator may be defined
by \( \hat{Z}_c = \hat{B} + \hat{S} \) with the baryon number operator \( \hat{B} \) and the strangeness number operator \( \hat{S} \) just as the hypercharge operator is defined by \( \hat{Y} = \hat{B} - \hat{L} \) with the baryon number operator \( \hat{B} \) and the lepton number operator \( \hat{L} \). Color charge quantum numbers for the proton and neutron are shown in Table I where the subscript \( d \) denotes the colorspin doublet and the subscript \( s \) denotes the colorspin singlet. Nucleons as the color spin doublet are governed by the \( SU(2)_L \times U(1)_Y \) gauge theory just as leptons or quarks as the isospin doublet are governed by the \( SU(2)_L \times U(1)_Y \) gauge theory in weak interactions. The conservation of the baryon number is the consequence of the \( U(1)_Z \) local gauge theory just as the conservation of lepton number is the consequence of the \( U(1)_Y \) local gauge theory. Baryons are conserved as the colorspin doublet but are not conserved as the color singlet; this is analogous to the conservation of leptons as the isospin doublet but the nonconservation of leptons as the isospin singlet in weak interactions. The immediate result of the proton number conservation or the baryon number conservation is shown in the mass density and charge density of nuclear matter. The effective charge unit of the charge operator \( \hat{q}_f = \hat{q}_f^{el} = \sqrt{2} \alpha_s / 64 \) while the electric charge unit of the charge operator \( \hat{q}_c = e = \sqrt{3} \alpha_s / 4 \) is the absolute magnitude of \( \hat{q}_f^{el} \) is the same with that of \( e \) since \( \alpha_s \approx 0.48 \) at the strong scale and \( \alpha_t \approx 0.12 \) at the weak scale.

Nuclear matter is quantized by the maximum wavevector mode \( N_F \approx 10^{26} \) in one dimension and the total baryon number \( B = N_B = 4 \pi N_F^3 / 3 \approx 10^{78} \) as the consequence of the baryon number conservation or the baryon asymmetry \( \delta_B \approx 10^{-10} \). Baryon matter quantization is consistent with the nuclear number density \( n_n = n_B = A / (4 \pi \xi^3 / 3) \approx 1.95 \times 10^{38} \text{ cm}^{-3} \) with the nuclear mass number \( A \) and the nuclear matter radius \( r \) at the strong scale \( M_G \approx 10^{-1} \text{ GeV} \) and is consistent with Avogadro’s number \( N_A = 6.02 \times 10^{23} \text{ mol}^{-1} \approx 10^{19} \text{ cm}^{-3} \) at the atomic scale. \( M_G \approx 10^{-8} \text{ GeV} \): The nuclear matter density is comparable to massive gluon density \( M_G^2 \approx 10^{38} \text{ cm}^{-3} \) at the strong scale and atomic matter density is also comparable to massive gauge boson density \( M_G^2 \approx 10^{19} \text{ cm}^{-3} \) at the atomic scale. This argument is also comparable with the nuclear number density \( n_B = 2k_F^2 / 3 \pi^2 \) with the Fermi momentum of a free nucleon \( k_F = 1.33 \text{ fm}^{-1} \) and the Fermi energy \( \epsilon_F = k_F^2 / 2m_n \approx 37 \text{ MeV} \) compatible with the nucleus radius

\[
r = r_0 A^{1/3} = r_0 n^2
\]

where the nucleon mass radius is \( r_0 = 1 / 2m_n \alpha_z \approx 1.2 \text{ fm} \) with the color degeneracy factor \( 2 \) and the principal quantum number \( n = A^{1/6} = B^{1/6} \) in analogy with the Bohr radius \( a_B = 1 / m_e \alpha_c \) of the hydrogen atom.

The Landé spin \( g \)-factors for the intrinsic magnetic dipole moment are \( g^p_s = 2 \mu_p / m_n = 5.59 \) for a proton and \( g^n_s = 2 \mu_n / m_n = -3.83 \) for a neutron where \( \mu_N = e / m_p = 3.15 \times 10^{-17} \text{ GeV} / T \) is the nuclear magneton. The \( g \)-factors are different with \( g_s = 2 \) for a pointlike electron and \( g_s = 0 \) for a pointlike neutral particle. The problem of the nuclear magnetic dipole moment suggests that contributions from colorspin and isospin degrees of freedom must be included to nucleons. The shifted values for the proton and neutron, 3.59 and \( -3.83 \) are almost identical and they mostly come from the combined contribution of colorspin and isospin. The mass ratio of the proton and the constituent quark, \( m_p / m_q \approx 2.79 \), also represents combined colorspin, isospin, spin degrees of freedom. The contribution \( |g_s| \approx 3.83 \) common for \( \mu_p \) and \( \mu_n \) comes from the magnetic dipole moment due to the \( SU(2)_N \times U(1)_Z \) symmetry for color charges and the \( SU(2)_L \times U(1)_Y \) symmetry for isospin charges while the contribution \( g_s \approx 1.76 \) only for \( \mu_p \) might come from the magnetic dipole moment due to the \( U(1)_f \) gauge symmetry. This interpretation is justified if the coupling constant \( g_f = \sqrt{e^f / \alpha_s} \approx \sqrt{\alpha_s / 16} \approx 1.7 \) for the \( U(1)_f \) gauge theory and the coupling constant \( g_b = \sqrt{e^b / \alpha_s} = \sqrt{\alpha_s / 3} \approx 3.8 \) for the \( SU(2)_N \times U(1)_Z \) gauge theory. The description above reflects the mixed contribution of colorspin, isospin, and spin degrees of freedom and the total angular momentum

\[
\vec{J} = \vec{L} + \vec{S} + \vec{I}
\]

and the extension of \( \vec{J} = \vec{L} + \vec{S} \).

Quantum numbers of nucleon-nucleon systems are summarized in Table II when colorspin degrees of freedom are taken into account in addition to isospin and spin degrees of freedom. Cross sections for the nucleon-nucleon (NN) scattering as an \( SU(2)_N \) gauge theory in terms of massive gluon exchange show excellent agreement with measurement data. According to conventional strong isospin invariance, three types of scattering such as the nn, pp, and pn scattering with strong isospin one (spin zero) exhibit almost the same cross sections. The cross section for the nn, pp, or pn scattering as a colorspin triplet is expressed by

\[
\sigma = \frac{4G_F^2 T^2}{\pi} \frac{1}{1 + 4 T^2 / M_G^2}
\]

in the center of mass energy \( T \) since \( m_n \mu_n \) in terms of the effective strong coupling constant \( G_R = \sqrt{2} \epsilon^f \alpha_s / 8 M_G^2 \). The theoretical cross section of the nn or pp scattering as an \( SU(2)_N \) gauge theory at high energies about from 2 GeV to 10 GeV is saturated to the experimental one of about 40 mb [1] and the cross section at low energies from 0.6 GeV to 2 GeV is roughly proportional to \( T^2 \): \( \epsilon^f = 1 / 4 \), \( \alpha_s = 0.48 \), \( M_G \approx 300 \text{ MeV} \), and \( G_R = 10 \text{ GeV}^{-2} \) are used in this evaluation. The symmetric \( SU(2)_N \) colorspin interaction for the isospin triplet and spin singlet contribution is commonly in-
volved in the above three types of nucleon-nucleon interactions with the massive gluon exchange.

The cross section in strong interactions as a \( U(1) \) gauge theory at relatively low energies can be nonrelativistically obtained using the Yukawa potential \( V(r) = \sqrt{G_f} \alpha_s e^{-M_G r}/r \):

\[
\sigma = 4\pi \frac{(c_f^2\alpha_s m_n)^2}{M_G^4} \frac{1}{1 + 4m_n T/M_G^2}
\]

(8)

where \( c_f^2 = -1/6 \) (or 1/12) is the asymmetric (symmetric) color factor, \( m_n = 0.94 \) MeV is the nucleon mass, \( T \) is the incident particle energy, and the gauge boson mass \( M_G \approx 140 \) MeV. The cross section data in the region below the energy 0.3 GeV or above the range 1.5 fm are obtained by using the above formula, which is definitely dependent on angular momenta. The calculated cross section data in the limit \( T \rightarrow 0 \) give agreement with observed data for cross sections \( (\sigma = 4\pi a^2) \) \( \sigma_{pp} \simeq \alpha_{nn} \simeq 35 \) b and \( \sigma_{pn} \simeq 66 \) b for spin singlet and \( \sigma_{pn} \simeq 4 \) b for spin triplet [2]. The effective (running) coupling constant \( \alpha_z = c_f^2\alpha_s = \alpha_s/16 \) becomes stronger at lower energies: \( \alpha_z = c_f^2\alpha_s \simeq 0.03 \) at about \( T = 100 \) MeV. The cross section difference in strong isospin triplet is mainly due to the contribution of colorspins: \( \sigma_{pn} \) has contributions from both colorspin triplet \( (c = 1) \) and colorspin singlet \( (c = 0) \) as shown in Table I. In the strong isospin triplet scattering \( (i^u = 1) \), almost the same cross section data are consequences of the similar invariant amplitude magnitude for color charged current and color neutral current mediated by color charged massive gluons \( (A^\pm) \) and neutral massive gluon \( (B^0) \), respectively, just as shown that the relative strength of the charged current and neutral current is the same in the GWS model [3]. It is thus emphasized that QND as the \( SU(2)_N \times U(1)_Z \) gauge theory produces the cross section data, which do not have divergence problems so that QND is renormalizable, from the zero energy limit to the order of 10^2 GeV.

In conclusion, QCD produces QND as the \( SU(2)_N \times U(1)_Z \) gauge theory for nuclear interactions and then produces the \( U(1)_f \) gauge theory for massless gauge boson (photon) dynamics. Comparison between QND and effective models is given in Table I. QND is applicable to various aspects in the wide energy range but effective models are only effective to few aspects of nuclear phenomena in the rather small energy range. The effective strong coupling constant \( G_f/\sqrt{2} = c_f^2 g^2/8M_G^2 \approx 10 \) GeV^{-2} like Fermi weak constant \( G_F/\sqrt{2} = g^2/8M_W^2 \approx 10^{-5} \) GeV^{-2} are used to study nuclear interactions. The proton number conservation is the result of the \( U(1)_f \) gauge theory and the baryon number conservation \( (B = N_B \approx 10^{78}) \) is the consequence of the \( U(1)_Z \) gauge theory for strong interactions: the charge quantization \( \tilde{Q}_f = \tilde{C}_f + \tilde{Z}_f/2 \) with the hyper-color operator \( \tilde{Z}_f = \tilde{B} + \tilde{S} \) for the \( U(1)_f \) gauge theory. The mass density and charge density of nuclear matter are the consequence of the proton number conservation or the baryon number conservation. The proton and neutron are assigned as a colorspin plus weak isospin doublet instead of as a strong isospin doublet. The extension of the total angular momentum \( \tilde{J} = \tilde{L} + \tilde{S} + \tilde{C} + \tilde{I} \) from \( \tilde{J} = \tilde{L} + \tilde{S} \) may explain the Lande spin-g-factors of magnetic dipole moments for the proton and neutron, \( g_p^Z = 5.59 \) and \( g_n^Z = -3.83 \), respectively. The cross sections of nucleon-nucleon scattering (pp, nn, or np) are compatible with QND as an \( SU(2)_N \times U(1)_Z \) gauge theory. More testable predictions or already confirmed predictions from QND are given as follows: parity violation in meson and baryon spectra, charge conjugation violation in baryon spectra, time reversal and CP violation in the electric dipole moment for the neutron \( (\Theta \leq 10^{-3}) \), the nonconservation of color singlet proton and neutron, the nonconservation of the axial vector current, strong coupling constant hierarchy, the color mixing angle \( \sin^2 \theta_R \approx 1/4 \), the assignment of strong isospin as colorspin plus weak isospin. Furthermore, QND possessing colorspin degrees of freedom may be successful in explaining the various nuclear phenomena such as lifetimes and cross sections of nuclear scattering and reaction, shell model, meson-nucleon scattering, nuclear potential, nuclear binding energy, gamma ray, etc. over the wide energy range [3].

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**TABLE I. Color Quantum Numbers of Nucleons**

| Baryons | $C$  | $C_3$ | $Z_3$ | $Q_f$ |
|---------|------|-------|-------|-------|
| $p_d$   | 1/2  | 1/2   | 1     | 1     |
| $n_d$   | 1/2  | −1/2  | 1     | 0     |
| $p_s$   | 0    | 0     | 2     | 1     |
| $n_s$   | 0    | 0     | 0     | 0     |

**TABLE II. Quantum Numbers of Nucleon-Nucleon Systems ($i^s$: strong isospin, $i$: weak isospin)**

| State | $i^s = 1$ | $i^s = 0$ |
|-------|-----------|-----------|
| $pp$  | $i = 1$, $s = 0$, $c = 1$ |
| $nn$  | $i = 1$, $s = 0$, $c = 1$ |
| $pn$  | $i = 1$, $s = 0$, $c = 1$, $i = 0$, $s = 1$, $c = 0$ |
|       | $i = 1$, $s = 1$, $c = 0$, $i = 0$, $s = 0$, $c = 1$ |
| Classification                                      | QND                      | Effective Models |
|----------------------------------------------------|--------------------------|------------------|
| Exchange Particles                                 | massive gluons           | model dependent  |
| DSSB                                               | yes                      | no               |
| Discrete symmetries (P, C, T, CP)                  | breaking                 | no               |
| Confinement                                        | yes                      | no               |
| Θ vacuum                                           | yes                      | no               |
| Baryon number conservation                         | $U(1)_B$ gauge theory ($N_B \simeq 10^{78}$) | unknown          |
| Proton number conservation                         | $U(1)_P$ gauge theory    | unknown          |
| Nuclear electromagnetic interaction                 | $U(1)_E$ gauge theory    | no               |
| Intrinsic angular momenta                          | colorspin, weak isospin, spin | spin            |
| Hadron mass generation                             | yes                      | unknown          |
| NN scattering cross section                         | $G^2_{NN}T^2$ (from high to low energy) | only at low energy |
| Hadron decay time                                   | $1/G_{NN}^2m^2_{NN}$     | no               |
| Neutron electric dipole moment                      | $\Theta \simeq 10^{-12}$ | no               |
| Free parameters                                    | coupling constant        | many             |
| Renormalization                                    | yes                      | model dependent  |