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# Nuclear force in the Skyrme model

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A generalized Skyrme model of the nucleon supplemented by possible extra terms in the Skyrme Lagrangian is applied to the study of the two-nucleon system. A variational approach taking account of modification of the chiral profile is employed. An adiabatic N-N potential is calculated by the standard spin-isospin projection technique. Several different approaches and parameter choices are examined and compared with each other. No medium-range attraction is found. Modification of some nucleon properties in the interacting system is investigated.

## I. INTRODUCTION

The $1/N_c$ expansion of quantum chromodynamics[1] has led to a renewed interest in the Skyrme soliton model for the baryon.[2,3] Phenomenological aspects of the Skyrme model have been explored. The calculated static properties of the nucleon come out within about 30% of experimental values.[4] The $\pi$N scattering phase shifts have been calculated in various partial waves,[5] and they reproduce the general characteristics of the experimental $\pi$N scattering data. An adiabatic nucleon-nucleon potential has been calculated,[6–12] and compared with the conventional meson exchange potentials. It has been found that the Skyrme model leads to a one-pion exchange potential at large $R$ and short-range strong repulsion, while it fails to explain medium-range attraction, which binds nucleons into a nucleus. The latter is the most serious difficulty in applying the Skyrme model to the multibaryon system.

The aim of this report is to introduce a variational approach to the two-skyrmion system and to seek a possible source of medium-range N-N attraction. We are also interested in the ability of the Skyrme model in studying possible modification of single nucleon properties in the interacting system. In a previous paper,[10] we have shown that modification of the chiral profile in the two-soliton system is significant. It lowers the soliton-soliton adiabatic potential and deforms the baryon density distribution drastically. In the present study, we incorporate spin-isospin quantization, which allows us to project the realistic NN potential out of the soliton-soliton potential. We also take into account several non-Skyrme terms in the Lagrangian. One of them has been claimed to produce attraction between two nucleons.[11]

In Sec. II, after a brief introduction to the generalized Skyrme model, a variational approach, called the scaling product approximation, is introduced and the spin-isospin projections are formulated. Various possible approaches are discussed. In Sec. III, we present results of the two-skyrmion calculation, comparing approaches and parameter choices. In Sec. IV, a brief summary and discussion are given.

## II. FORMULATION

We start with the generalized Skyrme Lagrangian in chiral SU $(2)\times$SU(2) theory, given in terms of the SU(2) matrix $U$ by

$$\mathcal{L}=\mathcal{L}_2+\mathcal{L}_4+\mathcal{L}_4'+\mathcal{L}_6+\mathcal{L}_m \ , \tag{1}$$

$$\mathcal{L}_2=-\frac{F_\pi^2}{16}\,\mathrm{Tr}\{L_\mu L^\mu\} \ , \tag{2}$$

$$\mathcal{L}_4=\frac{1}{32e^2}\,\mathrm{Tr}\{[L_\mu,L_\nu]^2\} \ , \tag{3}$$

$$\mathcal{L}_4'=\frac{\gamma}{8e^2}(\,\mathrm{Tr}\{L_\mu L^\mu\})^2 \ , \tag{4}$$

$$\mathcal{L}_6=-\frac{\beta^2}{2m_\omega^2}B_\mu B^\mu \ , \tag{5}$$

$$\mathcal{L}_m=\frac{m_\pi^2F_\pi^2}{8}\,\mathrm{Tr}\{U-1\} \ , \tag{6}$$

*with*

$$L_\mu=U^\dagger\partial_\mu U \tag{7}$$

and

$$B^\mu=\frac{1}{24\pi^2}\epsilon^{\mu\nu\sigma\rho}\,\mathrm{Tr}\{L_\nu L_\sigma L_\rho\} \ . \tag{8}$$

The first two terms $\mathcal{L}_2$ and $\mathcal{L}_4$ were chosen by Skyrme in his original work.[2] $\mathcal{L}_2$ is the pion kinetic energy term, and is known as the lowest order term in the effective low energy chiral meson theory. $\mathcal{L}_4$ was introduced by Skyrme to stabilize the soliton solution. $\mathcal{L}_4'$ is an additional fourth order derivative term, which is claimed necessary to reproduce the low energy $\pi\pi$ interaction.[13] $\mathcal{L}_6$ is the large $\omega$-mass limit of the $\omega$-soliton coupling term,[14] where $B_\mu$ is the conserved topological baryonic current. $\mathcal{L}_m$ is the pion mass term, which breaks the chiral symmetry explicitly. Equation (1) is, in fact, the most general Lagrangian so far discussed, except for introduction of explicit (finite mass) meson degrees of freedom besides the pion,[15] although it is not the unique choice in the low energy expansion of the effective chiral theory.[16]

The skyrmion is a static $B=1$ solution with hedgehog symmetry,

$$U(\mathbf{r})=U_h(\mathbf{r})=\exp[i\tau\cdot\hat{\mathbf{r}}F(r)] , \tag{9}$$

where the chiral profile $F(r)$ satisfies the boundary conditions, $F(r=0)=\pi$ and $F(r=\infty)=0$. $U_h$ does not have a definite spin nor isospin because the isospin of the pion field is correlated with the spatial coordinate $\mathbf{r}$. To obtain physical baryon states, one needs to superpose degenerate static soliton solutions given by the hedgehog (9) rotated in isospin space. Following Adkins, Nappi, and Witten,[4] we introduce collective rotation variables,

$$A\equiv a_4+i\mathbf{a}\cdot\tau , \tag{10}$$

with $\sum_{\mu=1}^{4}a_\mu^2=1$, and represent the physical baryon ($B=1$) solution by

$$U_1(\mathbf{r},A)=AU_h(\mathbf{r})A^\dagger . \tag{11}$$

By quantizing $a_4$ and $\mathbf{a}$ as collective coordinates, we obtain the spin-isospin wave function for a physical state, i.e., N or $\Delta$.[7,17]

It is easy to prove that a product $U=U(1)U(2)$ gives a $B=2$ configuration when $U(1)$ and $U(2)$ are $B=1$ fields.[2] We are interested in two baryon systems with a (fixed) relative distance $R$. We introduce a relative coordinate $R$ by

$$U(\mathbf{r})=U_1(\mathbf{r}-\mathbf{R}/2,\ A)U_1(\mathbf{r}+\mathbf{R}/2,\ B) , \tag{12}$$

with $U_1$ given by Eq. (11). This is an ansatz first proposed by Skyrme[2] and used in previous studies of the NN interaction.[6-12] Jackson *et al.*[6] and Vinh Mau *et al.*[7] calculated the energy of the NN system adiabatically by using the form (12). They found a strong central repulsion as well as a weak spin-dependent force, which is consistent with the one-pion exchange potential. It was assumed that the soliton profile $F$ does not change under the interaction. This approximation, which we call the free product approximation (FPA), is valid for large $R$. The validity, however, has been questioned in general for smaller $R$.[18,19]

The form (12) becomes more general if one allows deformation of the single soliton field $U_1$. The simplest generalization is to make the chiral profile $F$ dependent on $R$, keeping the spherical shape. Then $F(r,R)$ may be determined variationally for each $R$. In a previous report,[10] we have shown that this generalization changes the adiabatic skyrmion-skyrmion potential and the baryon density distribution in the two-skyrmion system significantly. For simplicity, we choose $A=B=1$ for a while and therefore consider the interaction between two unrotated hedgehog solitons. The static energy $E(R)$ calculated for

$$U(\mathbf{r})=U_h(\mathbf{r}-\mathbf{R}/2)U_h(\mathbf{r}+\mathbf{R}/2) \tag{13}$$

is a functional of $F$ and $F'$. Minimizing $E(R)$ for a fixed $R$, we obtain an integrodifferential equation for $F$, which is solved numerically. This approach we call the variational product approximation (VPA). Figure 1 shows the resulting soliton-soliton potential and the size of the individual soliton as a function of $R$ for the original Skyrme model, i.e., $m_\pi=0$ and $\gamma=\beta=0$ in the Lagrangian (1).[10] Although the energy gain by the variation is not large ($\leq 100$ MeV), the soliton size changes significantly. In Ref. 10 we also showed that the baryon density distribution is modified drastically. The large deformation is not surprising because the lowest excitation energy of the soliton, $\approx 200$ MeV, is less than the magnitude of the repulsion obtained. We conclude that the soliton is easily deformed when it is interacting.

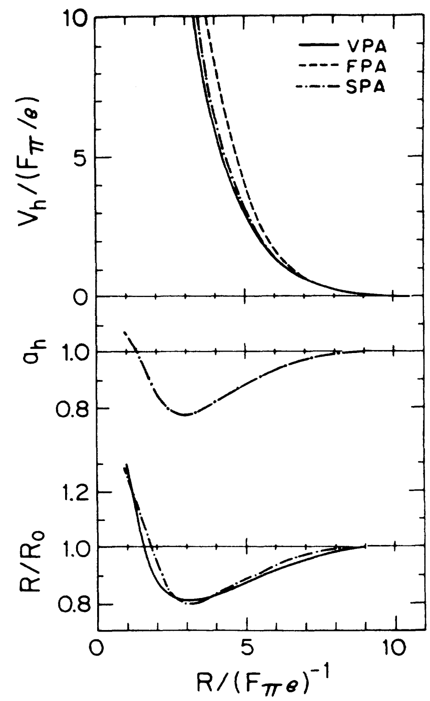


FIG. 1. Unrotated ($C=1$) soliton-soliton potential $V_h$, scaling parameter $a_h$, and the ratio of the soliton size vs $R$ for the original Skyrme model, i.e., $m_\pi=\beta=\gamma=0$ in the Lagrangian (1) (Ref. 10). The FPA (free product approximation) curve is obtained by using the free soliton solution in Eq. (13), and the VPA (variational product approximation) uses the solution of the differential equation for each $R$. The SPA is obtained by the scaling of $F(r)$ [Eq. (14)]. Standard values of the parameters (taken from Ref. 4) are $F_\pi=129$ MeV and $e=5.45$. The corresponding scales of length and energy are $(F_\pi e)^{-1}=0.28$ fm and $F_\pi/e=23.7$ MeV, respectively. The results with and without pion mass show no qualitative difference from each other.

The deformation of the chiral profile $F$ observed in the VPA is found to be mostly an overall scaling. To see this, we introduce a scale parameter $a(R)$ by the substitution

$$F(r,R)=F_0(r/a(R)) , \tag{14}$$

where $F_0$ is a free solution. Then the energy of the two soliton system is obtained as a function of the scale parameter $a$. The energy is minimized variationally for each fixed $R$ and the resulting chiral profile and the energy are compared with the VPA. The dashed-dotted curve in Fig. 1 shows the result in this approximation, which we call the scaling product approximation (SPA). One sees that the VPA solutions are almost recovered only by the scaling. Thus, without solving the differential equation, we obtain a deformed profile of the interacting solitons by the scaling.

In order to obtain the physical NN interaction out of the soliton-soliton interaction, one needs to quantize the rotation coordinates $A$ and $B$ given in Eqs. (11) and (12). The complete treatment of the rotations in the interacting system could involve a large amount of computation.[20] Instead, here we adopt a perturbative treatment following Vinh Mau *et al.*[7] The adiabatic energy for fixed $R$ is calculated for a *constant* $A$ and $B$, which happens to be a function only of $C \equiv c_4 + i\tau\cdot\mathbf{c} \equiv A^\dagger B$. The vector $\mathbf{c}$ behaves as a 3-vector in ordinary coordinate space and the adiabatic potential is a function of $c_4^2$, $(\mathbf{c}\cdot\hat{\mathbf{R}})^2 (\hat{\mathbf{R}} = \mathbf{R}/R)$ and $R$,

$$\begin{aligned} V(C,\mathbf{R}) &\equiv E(C,\mathbf{R}) - 2E_0 \\ &= V_1 + V_2 c_4^2 + V_3(\mathbf{c}\cdot\hat{\mathbf{R}})^2 + V_4 c_4^4 \\ &\quad + V_5 c_4^2 (\mathbf{c}\cdot\hat{\mathbf{R}})^2 + V_6(\mathbf{c}\cdot\hat{\mathbf{R}})^4 , \end{aligned} \tag{15}$$

where $E_0$ is the single soliton mass without the rotational kinetic energy, and the $V_i$'s are functions of $R$. Then the adiabatic potential is evaluated, using the free nucleon spin-isospin wave function, $\Psi_\alpha(A)$, $\alpha$ being the spin-isospin quantum number:

$$\begin{aligned} V_{\alpha\beta,\alpha'\beta'}(\mathbf{R}) = \int & \Psi_\alpha^\dagger(A)\Psi_\beta^\dagger(B) V(C = A^\dagger B, \mathbf{R}) \\ & \times \Psi_{\alpha'}(A)\Psi_{\beta'}(B)\, dA\, dB , \end{aligned} \tag{16}$$

where $dA$ ($dB$) stands for the integral over the three-dimensional sphere, $\sum_{\mu=1}^4 a_\mu^2 = 1$ ($\sum_\mu b_\mu^2 = 1$). By rearranging $V_{\alpha\beta,\alpha'\beta'}$ for various spin-isospin channels, one obtains three components of the NN potential, i.e., the isoscalar spin-independent central force $V_c$, the isovector spin-spin force $V_s$, and the isovector tensor force $V_t$.[7] Previous calculations have shown that the latter two isovector pieces, $V_s$ and $V_t$, coincide with the one-pion exchange potential at large $R$.

In applying the spin-isospin quantization in our approach, we have to note the order of modification of the chiral profile $F$ and the spin-isospin projection. Because the static energy depends on the relative rotational angle, $C = A^\dagger B$, we cannot neglect the rotation when we minimize the static energy. A possible solution is to project the spin and the isospin first and then to minimize, for instance, the NN central potential $V_c$ against $\delta F$. This seems a reasonable way if the solitons are rotating fast enough that the "static" energy is given by an average over the rotation. It is, however, not a unique solution. In fact, we cannot solve this problem in a fully consistent way without employing a complete quantization process by taking both the nonstatic and the static energy terms of the rotations into account simultaneously.[20] In the present study, however, we do not seek the complete solution because it requires a much harder computation. We instead employ three different approaches: minimize (1) the isoscalar central NN potential $V_c$, (2) the unrotated ($C=1$) soliton-soliton potential $V_h$, and (3) the soliton-soliton potential $V_r$ with a special rotation given by $c_4 = 0$, $\mathbf{c}\cdot\hat{\mathbf{R}} = 0$. The second choice, $V_h$, is the one discussed above and happens to be the most repulsive potential. The third choice, $V_r$, gives the most attractive potential, reached by rotating one of the skyrmions by 180° around an axis perpendicular to $\hat{\mathbf{R}}$.[6] These three potentials are given explicitly in terms of the $V_i$'s in Eq. (15) by

$$\begin{aligned} V_c &= V_1 + \tfrac{1}{4}(V_2 + V_3) + \tfrac{1}{8}(V_4 + V_6) + \tfrac{1}{24} V_5 , \\ V_h &= V_1 + V_2 + V_4 , \\ V_r &= V_1 . \end{aligned} \tag{17}$$

By choosing the above three cases, we explore the whole range of the static interaction to be minimized against $\delta F$. In the next section we present the results obtained by minimizing $V_c$ (SPAc), $V_h$ (SPAh), or $V_r$ (SPAr) variationally in the scaling approximation (SPA).

## III. RESULTS

One of the purposes of the present study is to show the roles of $\mathcal{L}_4'$ and $\mathcal{L}_6$ terms in the two-skyrmion system. We choose two sets of parameters and compare the results. The first one is (I) $\beta = \gamma = m_\pi = 0$, $F_\pi = 129$ MeV and $e = 5.45$, which gives the original Skyrme model. The parameter values are taken from Ref. 4. The masses of the baryons are $M_{\mathrm{N}} = 936$ MeV and $M_\Delta = 1229$ MeV and $\langle r^2 \rangle_{I=0}^{1/2} = 0.59$ fm. Because $F_\pi$ is the only dimensional parameter, the results for other values of $F_\pi$ and $e$ are easily found by scaling of the length by $(F_\pi e)^{-1}$ ($=0.28$ fm for the present choice) and the energy by $F_\pi / e$ ($=23.7$ MeV).

In the second choice we take all the terms of the Lagrangian (1) into account. It is known that $\mathcal{L}_4'$ with a positive $\gamma$, which is consistent with the low energy $\pi\pi$ interaction, destabilizes the soliton, while the $\mathcal{L}_6$ term is always repulsive and stabilized the soliton. In fact, introduction of $\mathcal{L}_4'$ without $\mathcal{L}_6$ is disastrous, especially in multisoliton systems.[21] Qualitatively, increase of $\beta$ of $\mathcal{L}_6$ makes the soliton expand, while increase of $\gamma > 0$ of $\mathcal{L}_4'$ makes the chiral profile $F(r)$ oscillate around $r \approx 2\text{–}3$ $(F_\pi e)^{-1}$. The latter causes instability of the soliton and for large $\gamma$ one cannot find a solution. This qualitative tendency is enhanced in multisoliton systems. Contributions to the static energy of the soliton from $\mathcal{L}_4'$ and $\mathcal{L}_6$ tend to cancel with each other. When the contributions of those terms become comparable with those of $\mathcal{L}_2$ and $\mathcal{L}_4$, the results would become very sensitive to the parameter choice. To avoid this unfavorable situation, we prefer moderate magnitudes of $\beta$ and $\gamma$.

We choose the second parameter set according to Ref. 12: (II) $F_\pi = 164$ MeV, $e = 7.0$, $m_\pi = 137$ MeV, $\gamma = 0.12$, and $\beta = 3.5$, which is claimed to minimize the central potential in the free product approximation (FPA). In this choice the contribution of $\mathcal{L}_4'$ and $\mathcal{L}_6$ in the single soliton static energy is less than half of that of $\mathcal{L}_2$ and $\mathcal{L}_4$, while any larger values of $\beta$ and $\gamma$ would make the results too sensitive to the parameter choice. The masses of the baryons are $M_{\mathrm{N}} = 1053$ MeV and $M_\Delta = 1787$ MeV, which indicates that the moment of inertia is too small to fit to experiment. The baryonic rms radius $\langle r^2 \rangle_{I=0}^{1/2} = 0.42$ fm.

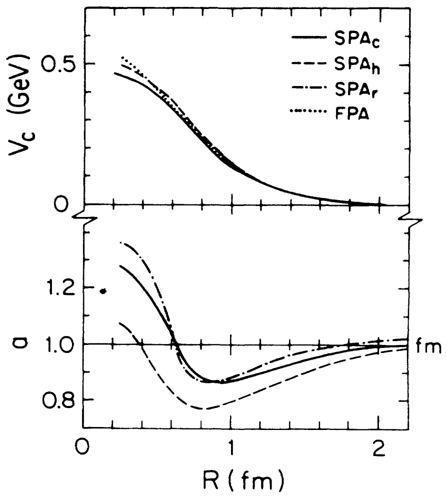


FIG. 2. Isoscalar central NN potential and the scaling parameter $a$ in various approximations (see text) for the parameter set (I). The SPAr result coincides with the SPAc one.

Figures 2 and 3 summarize the results for the two-soliton calculation. $a(R)$ is the scaling parameter defined by Eq. (14) in the scaling product approximation (SPA). SPAc, SPAh, and SPAr stand for, respectively, the SPA with $V_c$, $V_h$, and $V_r$ [Eq. (17)] minimized.

One notices that there exists no attraction in the central potential, although the introduction of the $\mathcal{L}_4'$ term has been suggested to bring NN attraction.[11,22] The energy contributions from $\mathcal{L}_4'$ and $\mathcal{L}_6$ tend to cancel with each other for the two-soliton system as well as for the single soliton. For instance, contributions to the single soliton energy are 516 MeV from $\mathcal{L}_2$, 383 MeV from $\mathcal{L}_4$, $-164$ MeV from $\mathcal{L}_4'$, 117 MeV from $\mathcal{L}_6$, and 181 MeV from $\mathcal{L}_m$ for parameter set (II). As is stressed above, the contributions from $\mathcal{L}_4'$ and $\mathcal{L}_6$ are less than a half of those from $\mathcal{L}_2$ and $\mathcal{L}_4$. At $R=0.86$ fm $[=5\,(F_\pi e)^{-1}]$, the adiabatic central potential $V_c$ consists of $-69$ MeV from $\mathcal{L}_2$, 217 MeV from $\mathcal{L}_4$, $-124$ MeV from $\mathcal{L}_4'$, 169 MeV from $\mathcal{L}_6$ and $-9$ MeV from $\mathcal{L}_m$. We do not see any significant extra attraction due to the scaling variation in the central potential at $R>0.5$ fm, while in the unrotated soliton-soliton potential $V_h$ has 50–100 MeV more attraction in the same region. In fact, a difference of $V_c$ among SPAc, SPAh, and SPAr is little, except for $R<0.5$ fm. For

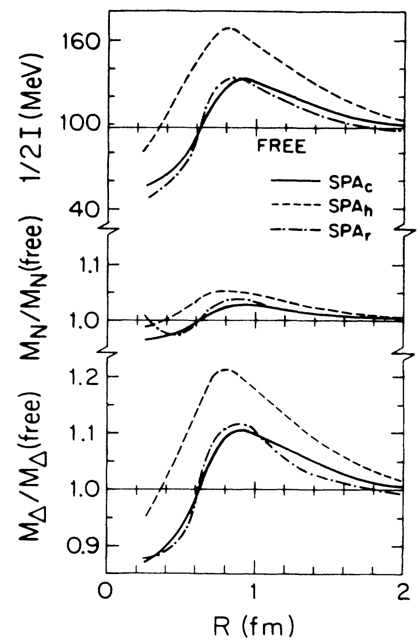


FIG. 4. Rotational kinetic energy, $1/2\mathcal{I}$, $\mathcal{I}$ being the moment of inertia, and the ratio of the nucleon and the $\Delta$ masses to the corresponding free masses, respectively, for parameter set (I).

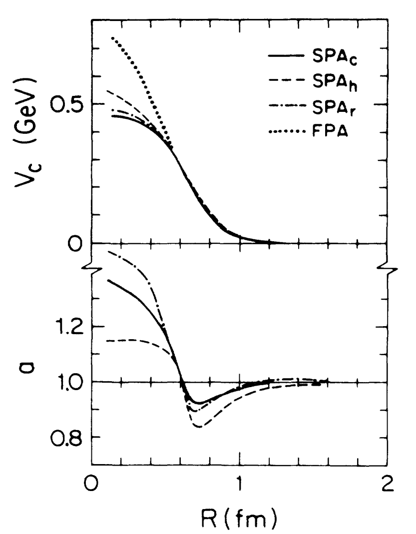


FIG. 3. The same as Fig. 2 for parameter set (II).

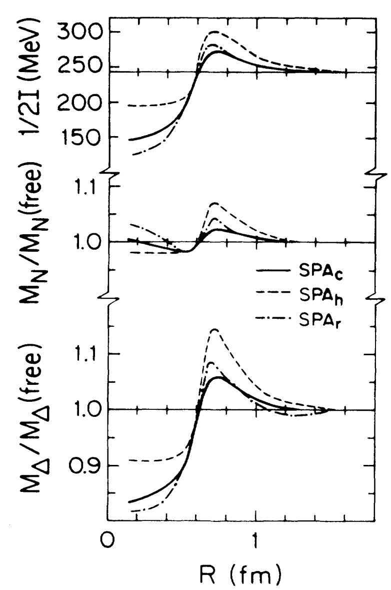


FIG. 5. The same as Fig. 4 for parameter set (II).

$R < 0.5$ fm, a significant energy gain is observed in the variation. The main difference between parameter choices (I) and (II) is the range of the potential. For (II), the range is shorter and the potential rise is sharper than for (I), while the magnitude of the central repulsion is about the same.

It is known that the contribution of $\mathcal{L}_4$ to the central NN potential $V_c$ is even under the $G$-parity transformation.[6–9] ($G$-parity decomposition for the potential can be done by comparing the $\mathrm{N\bar{N}}$ potential with the NN one.) In the generalized Lagrangian, contribution of $\mathcal{L}_6$ to $V_c$ is $G$-parity odd and, in fact, about one-third or one-fourth of the total $V_c$ is found to be $G$-parity odd at $R \approx 0.5-1$ fm in the present calculation.

We are also interested in single baryon properties in the interacting system. Here we choose three of them: moment of inertia, masses of $N$ and $\Delta$, and the axial coupling constant $g_A$. These quantities in the interacting system are defined by the corresponding values for a single soliton with the scaling replacement (14). $M_N$ and $M_\Delta$ include the rotational energy calculated by the use of the modified moment of inertia $I(R)$. One sees in Figs. 4 and 5 that both $M_{\mathrm{N}}$ and $M_\Delta$ are enhanced at $R > 0.5$ fm by $\approx 5\%$ for N and $\approx 15-20$ % for $\Delta$. This is due to the increase of the soliton mass and the reduction of the moment of inertia $I$ along with the scaling parameter $a$, roughly $I \approx a^2$. The $R$ dependence of the moment of inertia induces an effective interaction, which amounts up to $\approx 50-100$ MeV of repulsion for NN at around $R \approx 1$ fm. This significant repulsion raises a question on the treatment of the rotational energy as a higher order effect (in $1/N_c$). If we include the rotational energy in the potential minimized variationally, we would expect significant interference between the internal motion and the global rotational energy. Qualitatively, this effect will enhance the size of the soliton to reduce the rotational energy. We also observe a reduction of $g_A$ by 15–20 % at $R \approx 1$ fm. This is again due to the reduction of $a(R)$, because $g_A$ is proportional to $a$.

We observe $a_r > a_c > a_h$ for $R > 1$ fm region, which seems to (anticorrelate) with the static potentials, $V_r < V_c < V_h$. In fact, this is consistent with a general argument that there exists a simple relation between the long-range potential and the size of the soliton.[23] According to the general theorem, the soliton size grows when the intersolitonic interaction is attractive, while it shrinks when repulsive. We observe a 10%–20 % decrease in the scale parameter at $R \approx 0.5-1$ fm. The size of the single soliton $\langle r^2 \rangle_{I=0}^{1/2}$ behaves almost identically in this region.

## IV. SUMMARY AND DISCUSSION

In summary, we have studied the two-nucleon system in the generalized Skyrme model of the baryon, where the symmetric quartic derivative term $\mathcal{L}_4'$ as well as the sixth order derivative term $\mathcal{L}_6$ is included. Modification of the chiral profile is taken into account by a scale variation. There is no attraction found in the NN central force, because of the cancellation of the $\mathcal{L}_4'$ attractive contribution by the strong $\mathcal{L}_6$ repulsion. We have shown that single nucleon properties are also modified in the interacting system. The nucleon mass is enhanced at $R > 0.5$ fm, and the nucleon size decreases in the same region. We also found that the $R$ dependence of the moment of inertia is significant at $R \approx 1$ fm. The effective NN interaction due to this change seems significant so as to make coupling between the rotation and the internal motion important. These results are necessarily qualitative because, first, the Skyrme model provides single nucleon properties with typically 10–20 % errors, and, secondly, it cannot reproduce medium range NN attraction. The latter is serious, because at large $R$, turning the repulsion into an attraction could change the behavior of the scale parameter $a$. It is also noted that the variational approach used here would not be valid at short distances (say $R < 0.5$ fm), where one could expect a large deformation not covered by the overall scaling.

Much discussion has been devoted to possible sources of the attraction. In Ref. 19, the authors took a larger space for the energy variation, but they could not find enough attraction. In Ref. 24, semiclassical treatment of the relative skyrmion motion was discussed. The effect, of higher order in $1/N_c$, was found to be significant at high energy, while it failed to provide an attraction at low energy. Another possibility lies in the rotational motion of the skyrmion. In the conventional meson exchange picture, the two-pion exchange with N$\Delta$ or $\Delta\Delta$ intermediate states is known to dominate the medium range attraction. In the Skyrme model, $\Delta$ is treated as a rotational excited state of the nucleon. Adiabatic calculation with the N$\Delta$ and $\Delta\Delta$ coupled to NN channels does not show significant attraction.[12,25] Because the rotational energy is of higher order in $1/N_c$ a careful and proper treatment of higher order effects seems important. The problem is still open.

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