# Relativistic effect on the deformation of $\Delta(1232)$ in a chiral quark model

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Relativistic corrections in the electromagnetic transition operators for the $E2/M1$ ratio in the $\gamma N \rightarrow \Delta$ process are investigated based on a chiral quark model. The improved result shows that the effect of the relativistic corrections plays a desirable role in the ratio when compared with our previous calculation. [S0556-2813(98)00301-X]

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## I. INTRODUCTION

Electromagnetic transitions between the nucleon and its excited states, baryon resonances, are important probes for understanding the baryon structures. Now, investigation of the spin-dependent structure functions of nucleons in the resonance region provides a new reason to study baryon electromagnetic properties. Besides the Ellis-Jaffe sum rule, there is the Drell-Hearn-Gerasimov (DHG) sum rule [1] which can be tested in the limit $Q^2 \rightarrow 0$ ($Q^2$ is momentum transfer) by absorbing transverse polarized photons on polarized nucleons. This model-independent sum rule connects the helicity structure of the cross sections in the inelastic region with ground state properties [2]. We know that the DHG sum rule is almost saturated by the low lying resonances, such as $\Delta(1232)$ [3–5]. Therefore, to test the DHG sum rule, we need to understand the baryon properties in the low-energy range. In addition, a study of the $\Delta(1232)$ properties provides valuable hints about the quark-quark interaction as well as the magnitude of the $D$-state admixture [6], which indicates the presence of an oblate charge deformation, in the wave function. It imposes strong constraint for model-dependent calculations. Experiments at Mainz [7], SPring-8 [8], SLAC [9], and Jefferson Lab [10] are expected to provide new tests for various model-dependent calculations of the $\Delta(1232)$ properties, such as the $E2/M1$ ratio. Recently, the analysis of pion photoproduction in the $\Delta$ resonance region by Arndt, Strakovsky, and Workman [11] showed that the $E2/M1$ ratio is around $(-2.8 \pm 0.93)\%$. Their result and information from LEGS [12] about the $D$-wave admixture in the $\Delta(1232)$ and $P_{11}(938)$ wave functions have already provided a challenge for conventional quark model calculations.

It should be noted that most quark model investigations in the literature [13,14] used the impulse approximation to calculate the helicity amplitudes and the $E2/M1$ ratio for the $\Delta(1232)$. Their results for that ratio are much smaller than the experimental data [15]. As has been shown [16] this discrepancy is due mainly to the nonresonant meson exchange mechanism, which cannot be separated using just the process $\gamma N \rightarrow \Delta$. It implies the importance of a chiral meson field effect. An approximate way to realize the nonperturbative physics governed by chiral symmetry breaking in QCD is to assume that in the low- and intermediate-energy ranges a baryon is composed of constituent quark components and a meson cloud. It has been suggested that beyond the scale of spontaneous chiral symmetry breaking, a light or strange baryon can be regarded as a system of three constituent quarks interacting by the exchange of Goldstone bosons and confinement. This approach was first proposed by Manohar and Georgi in 1984 [17]. Since then, much work based on this idea has been published. The work of Glozman and Riska [18] and others [19] for baryon spectra has shown the advantage of the model. This constituent quark model was extended to investigate the baryon-baryon interaction [20,21] as well. Recently, a nonrelativistic chiral constituent quark model [22] was applied to study the deformation of $\Delta(1232)$ by Shen *et al.* Their result indicated that including the chiral meson field improved the theoretical prediction for the $E2/M1$ ratio. The important role of the chiral meson field was reflected in the $D$-wave admixture in the $\Delta(1232)$ wave function, which resulted from the tensor force of the Goldstone bosons exchange interaction. However, in this work, relativistic corrections to the electromagnetic transition operators of the quark-photon interaction were not included. From the quark model analyses in the literature [23–25], we know that the relativistic corrections, such as spin orbit and nonadditive [23] terms, are very important in generating the model-independent DHG and Schwinger sum rules and the low-energy theorem in Compton scattering. Therefore, in order to give a consistent description of the baryon transition properties, one should take the relativistic corrections into account.

In the well-known Isgur-Karl model or its relativistic version [13,14], we know that the $D$-wave admixture in the $\Delta(1232)$ wave function caused by the tensor force of the one-gluon exchange potential is not large enough to predict the ratio of the electric quadrupole to magnetic dipole amplitude $E2/M1$ in comparison with the data [15]. The investigation of Ref. [22] made us believe that the consideration of the tensor force coming from the Goldstone bosons exchange interaction could provide improved results for the ratio and other electromagnetic properties of the $\Delta(1232)$ in the low-energy region. In this paper, we shall reapply the chiral quark

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model [22] to calculate the $E2/M1$ ratio with the inclusion of the relativistic corrections in the electromagnetic transition operators, and moreover, predict $Q^2$-dependent behaviors of the $E2/M1$ and $C2/M1$ ratios for $\Delta(1232)$.

## II. CHIRAL QUARK MODEL

In our chiral constituent quark model, the Hamiltonian of a baryon is

$$H_B=B_0+\sum_i\left(m+\frac{\vec{p}_i^{\,2}}{2m}\right)+\sum_{i>j}\left(V_{ij}^{\mathrm{OGE}}+V_{ij}^{\mathrm{conf}}+V_{ij}^{\mathrm{chiral}}\right), \tag{1}$$

where, besides the conventional perturbative one-gluon exchange potential and confinement, the chiral meson exchange interaction between the constituent quarks, which represents nonperturbative physics, is

$$V_{ij}^{\mathrm{chiral}}=V_{ij}^{\pi}+V_{ij}^{\sigma} \tag{2}$$

with

$$\begin{aligned}V_{ij}^{\pi}=&\frac{g_{ch}^2}{4\pi}\frac{m_\pi^2}{12m^2}\frac{\Lambda^2}{\Lambda^2-m_\pi^2}m_\pi(\vec{\tau}_i\cdot\vec{\tau}_j)\\&\times\left(\left[Y(m_\pi r_{ij})-\frac{\Lambda^3}{m_\pi^3}Y(\Lambda r_{ij})\right](\vec{\sigma}_i\cdot\vec{\sigma}_j)\right.\\&\left.+\left[Y_2(m_\pi r_{ij})-\frac{\Lambda^3}{m_\pi^3}Y_2(\Lambda r_{ij})\right]S_{ij}\right),\end{aligned} \tag{3}$$

and

$$V_{ij}^{\sigma}=-\frac{g_{ch}^2}{4\pi}\frac{\Lambda^2}{\Lambda^2-m_\sigma^2}m_\sigma\left[Y(m_\sigma r_{ij})-\frac{\Lambda}{m_\sigma}Y(\Lambda r_{ij})\right], \tag{4}$$

where $\Lambda$(we choose $\Lambda=1$ GeV) is a cutoff parameter for regularizing the potential at short distances, $g_{\mathrm{ch}}$ is the chiral coupling constant, which can be fixed by an empirical $\pi NN$ coupling constant $g_{\mathrm{ch}}=(3m/5M_N)g_{\pi NN}(g_{\pi NN}^2/4\pi\simeq 14.2)$. In above equations, we introduce following notations [20]:

$$S_{ij}=3(\vec{\sigma}_i\cdot\hat{r}_{ij})(\vec{\sigma}_j\cdot\hat{r}_{ij})-\vec{\sigma}_i\cdot\vec{\sigma}_j, \tag{5}$$

$$Y(x)=\frac{e^{-x}}{x},\quad Y_2(x)=\left(1+\frac{3}{x}+\frac{3}{x^2}\right)Y(x). \tag{6}$$

In Eq. (1), the confinement is the conventional linear potential. The one-gluon-exchange interaction is

$$V_{ij}^{\mathrm{OGE}}=-\frac{2}{3}\alpha_s\left[\frac{1}{r_{ij}}-\frac{\pi}{m^2}\left(1+\frac{2}{3}\vec{\sigma}_i\cdot\vec{\sigma}_j\right)\delta(\vec{r}_{ij})-\frac{1}{4m^2r_{ij}^3}S_{ij}\right]. \tag{7}$$

Here, we mention that we do not include spin-orbit force, because it has been proved that this force could give out unacceptable results comparing with the data. The detail analysis of this force could be seen in Ref. [26]. So far, the study of the spin-orbit force is still an unsettled theoretical issue.

To calculate baryon spectra, we determine potential parameters as follows. First, we choose quark mass $m=0.35$ GeV and length parameter of the harmonic oscillator wave function $b=0.465$ fm. In such case, the first orbital excited state of the system is about 500 MeV higher than ground state. We determine strong coupling constant $\alpha_s$ by fitting the mass difference between the $\Delta(1232)$ and $P_{11}(938)$. It should be emphasized that if one uses the conventional Isgur-Karl model, only spin-spin contact term from the one gluon exchange interaction contributes to the mass difference, and the obtained strong coupling constant $\alpha_s\sim 1.15$. In our chiral quark model, on the other hand, the spin-spin interactions from both one gluon exchange and chiral field attribute to the mass difference and therefore, the strong coupling constant is suppressed to be $\alpha_s\sim 0.67$. This feature means that the chiral field plays a remarkable role on the interaction between quarks. Then, we apply the variational condition $\partial M_N/\partial b=0$ to define the strength of the confinement. Finally, within $N\leqslant 2$ harmonic oscillator wave function space, we calculate the baryon spectra and wave functions. Our calculation result converges well as the model space for the one-baryon Hamiltonian increases from $N\leqslant 2$ to $N\leqslant 4$.

In our analysis, we use the symbol $|B^{2S+1}X_J\rangle_\pi$ to denote a multiplet according to the underlying SU(6) spin-flavor symmetry, where $B=N$, $\Delta$ stands for the SU(3) representation (flavor octet or decuplet), ${}^{2S+1}X_J$ is the usual spectroscopic notation [with $X=S, P, D, \ldots,$ staying for $L$ and $J(S)$ for the total angular momentum (spin)], and $\pi=S, M,$ $A$ indicates the symmetry type of the SU(6) states (symmetric, mixed, and antisymmetric, respectively). Comparing the $\Delta(1232)$ and $P_{11}(938)$ wave functions in present calculation and the results in the conventional Isgur-Karl model, we confirm that the chiral meson field enlarges the $D$-wave admixture in the wave functions. The expansion coefficients of the $D$-wave configuration mixing: $|\Delta^4D_{3/2}\rangle_S$ and $|\Delta^2D_{3/2}\rangle_M$ increase about 25 and 45 % in the $\Delta(1232)$ wave function, respectively, and the coefficient of $|N^4D_{1/2}\rangle_M$ increases about 20% in the $P_{11}(938)$ wave function simultaneously. All these results mean that the chiral meson effect enhances the oblate deformation of $\Delta(1232)$ and $P_{11}(938)$.

The magnetic $M_{1+}$ (or $M1$) and electric $E_{1+}$ (or $E2$) transition amplitudes of the $\gamma N\to\Delta$ process have the following relations with the transverse helicity amplitudes [14]:

$$M_{1+}=-\frac{1}{2\sqrt{3}}(3A_{3/2}+\sqrt{3}A_{1/2}),$$

$$E_{1+}=\frac{1}{2\sqrt{3}}(A_{3/2}-\sqrt{3}A_{1/2}). \tag{8}$$

To calculate the transverse and longitudinal transition amplitudes, we use following transverse transition operators [27]

$$H_t=\sum_j \left\{ e_j\vec{r}_j\cdot\vec{E}_j-\frac{e_j}{2m_j}\vec{\sigma}_j\cdot\vec{B}_j -\frac{e_j}{4m_j}\vec{\sigma}_j\cdot\left[\vec{E}_j\times\frac{\vec{p}_j}{2m_j}-\frac{\vec{p}_j}{2m_j}\times\vec{E}_j\right]\right\} +\sum_{j<l}\frac{1}{4M}\left[\frac{\vec{\sigma}_j}{m_j}-\frac{\vec{\sigma}_l}{m_l}\right]\cdot(e_l\vec{E}_l\times\vec{p}_j-e_j\vec{E}_j\times\vec{p}_l), \quad (9)$$

where the electric and magnetic fields are defined as

$$\vec{E}_i=i\omega\sqrt{4\pi}\sqrt{\frac{1}{2\omega}}\vec{\epsilon}\,\exp(-\vec{k}\cdot\vec{r}_i),$$

$$\vec{B}_i=i\sqrt{4\pi}\sqrt{\frac{1}{2\omega}}\vec{\epsilon}\times\vec{k}\,\exp(-i\vec{k}\cdot\vec{r}_i). \quad (10)$$

In addition, the longitudinal current $J_0$ [25]

$$J_0=\sqrt{\frac{1}{2\omega}}\left\{\sum_j\left(e_j+\frac{ie_j}{4m_j^2}\vec{k}\cdot(\vec{\sigma}_j\times\vec{p}_j)\right)e^{i\vec{k}\cdot\vec{r}_j} -\sum_{j<l}\frac{i}{4M}\left(\frac{\vec{\sigma}_j}{m_j}-\frac{\vec{\sigma}_l}{m_l}\right)\cdot(e_j\vec{k}\times\vec{p}_l e^{i\vec{k}\cdot\vec{r}_j}-e_l\vec{k}\times\vec{p}_j e^{i\vec{k}\cdot\vec{r}_l})\right\}, \quad (11)$$

is also used to calculate the $C2/M1$ ratio. Clearly, in above operators, both the spin-orbit term [the third term of Eq. (9) and the second term of Eq. (11)] and nonadditive term [the last terms of Eqs. (9) and (11)] are included explicitly. The nonadditive term is associated with the Wigner rotation of the quark spins from the frame of the recoiling quark to the frame of the recoiling baryon [23,27]. These spin-orbit and the nonadditive terms in the transition operators are not considered in our previous nonrelativistic chiral quark model calculation [22]. It has been emphasized that these relativistic terms are very important in generating the model-independent DHG and Schwinger sum rules [24,25] in the limit $Q^2\to 0$ and the low-energy theorem in the Compton scattering. Therefore, the relativistic effect must be considered consistently.

## III. CONCLUSIONS

If one takes SU(6) symmetry for the wave functions of $\Delta(1232)$ and $P_{11}(938)$, which means no deformation in the wave functions, only the $M1$ transition amplitude is left and the $E2$ transition amplitude vanishes. This is because, in this symmetry limit, we have a constraint condition $A_{3/2}=\sqrt{3}A_{1/2}$. In addition, the longitudinal transition amplitude $S_{1/2}(S_{1/2}=\langle f,1/2|J_0|i,1/2\rangle)$ is zero too in this limit. Therefore, the consideration of the oblate deformation in the $\Delta(1232)$ and $P_{11}(938)$ wave functions, which result from the tensor force, is one way to predict the nonvanishing data of the $E2$ and $S_{1/2}$ amplitudes. To indicate that the tensor force of the one-gluon exchange interaction is not large enough in the conventional quark model calculations, we display some previous results [13,14,28–31] for the $E2/M1$ ratio in Table I. Clearly, all those results are much smaller than the data in the Particle Data Group $(-1.5\pm0.4)\%$ [15]. Recently, the new work of pion photoproduction in the $\Delta$ region [11] and the new analyses of Mainz group [32], and Davidson and Mukhopadhyay [33] all show that the magnitude of the ratio, which is around $-2.5\%$, might be even larger than the value in the Particle Data Group [15].

TABLE I. The $E2/M1$ ratio at $Q^2=0$ point in various quark model calculations.

| References | $E2/M1(\%)$ |
|---|---|
| Isgur, Karl, and Koniuk (Ref. [13]) | $-0.41$ |
| Capstick and Karl (Ref. [14]) | $-0.21$ |
| Gerstein and Dzhikiya (Ref. [28]) | $-0.32$ |
| Weyrauch and Weber (Ref. [29]) | $-0.69$ |
| Bourdeau and Mukhopadhyay (Ref. [30]) | $-0.6$ |
| Gogilidze, Surovstev, and Tkebuchava (Ref. [31]) | $-0.65$ |
| Result of Ref. [22] without the relativistic effect | $-1.09$ |
| Result of this work | $-1.40$ |
| Particle Data Group (Ref. [15]) | $-1.5\pm0.4$ |

In Table I, our calculation result for the $E2/M1$ ratio at $Q^2=0$ with the inclusion of the relativistic corrections in the electromagnetic transitions is listed in comparison with our previous result without the corrections [22] and other quark model calculations. To investigate the effect of the relativistic corrections in the transitions operators, we see that it plays a desirable role to the calculation of the $E2/M1$ ratio. Although, the effect does not significantly influence the magnitude of the magnetic $M1$ transition amplitude, it affects the $E2$ transition amplitude of $\Delta(1232)$ evidently. The predicted value of the $E2/M1$ ratio for the photoproduction increases from $-1.0$ to $-1.4$ %. In Figs. 1 and 2, our present calculations for the $Q^2$-dependent behaviors of the $E2/M1$ and $C2/M1$ ratios for the electroproduction in the equal velocity frame (EVF) [34] are plotted in comparison with the results of the Isgur-Karl model and our previous nonrelativistic chiral quark model calculation [22]. In the two figures, the data are taken from Refs. [35,36] and Refs. [36,37], respectively. From the figures, we find that the relativistic effect enlarges the magnitudes of these two ratios and plays a positive role as well when compared with the data. As a result, our improved predictions indicate that the relativistic effect is important for the determination of the electromagnetic properties of baryon resonances and it should be considered consistently.

Our present result for the $E2/M1$ ratio at $Q^2=0$ point is in qualitative agreement with the previous calculations of the chiral quark soliton model by Watabe *et al.* [38] and the linear $\sigma$ model and chiral chromodielectric model [39]. In Ref. [38], the NJL model was used to calculate the ratio for photoproduction. The effect of the pion cloud does not appear explicitly. It shows that the main oblate charge deformation is due to the Dirac sea which can be expressed in terms of the dynamical pion field. The estimated $E2/M1$ ratio of Ref. [38] was $-2.6\%$ which was close to the predic-

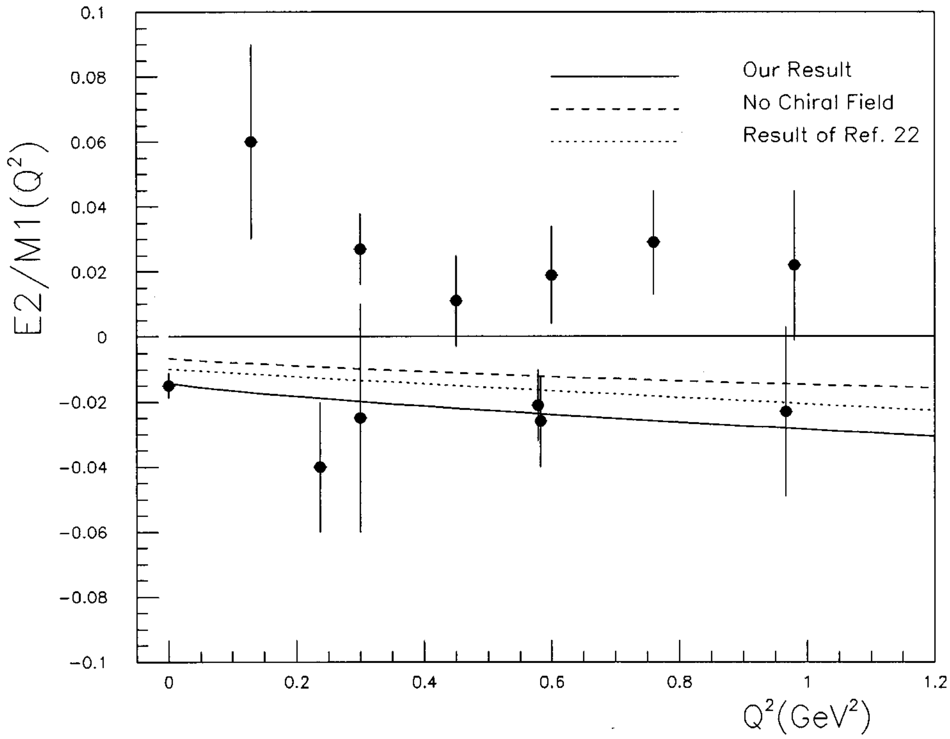


FIG. 1. $Q^2$-dependent behavior of the $E2/M1$ ratio. The solid, dashed, and dotted curves are the results of our present work, the conventional Isgur-Karl model, and Ref. [22] without including the relativistic corrections in the transition operators, respectively. Data are quoted from Refs. [35,36].

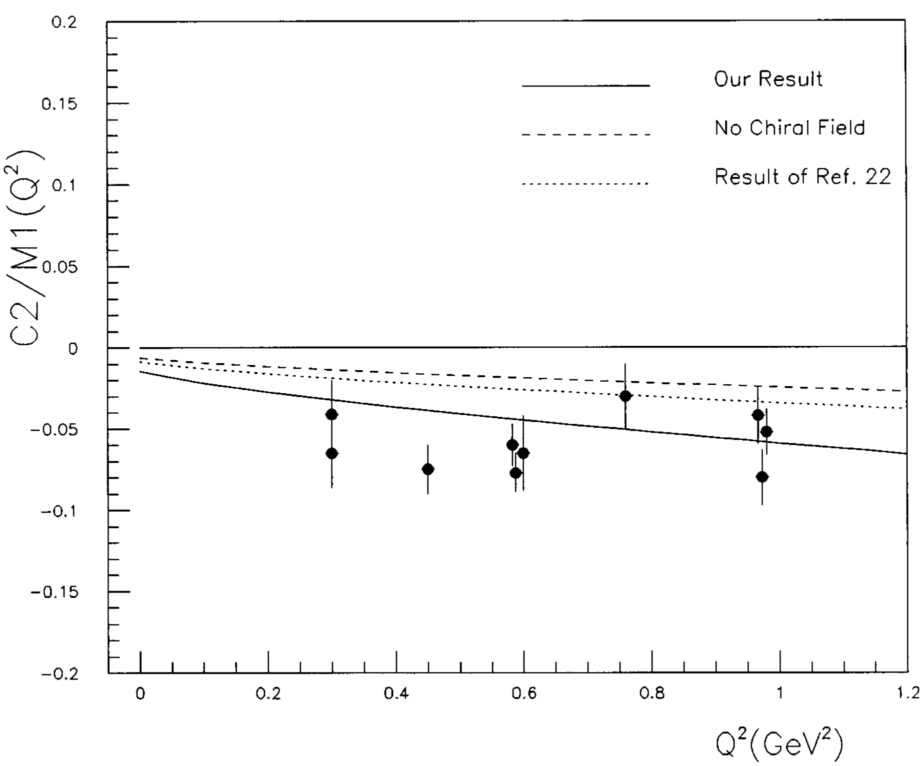


FIG. 2. $Q^2$-dependent behavior of the $C2/M1$ ratio. Key as in Fig. 1. Data are quoted from Refs. [36,37].

tion of Ref. [39]. It should be mentioned that, in our calculation, the calculated helicity amplitudes $A_{1/2}$ and $A_{3/2}$ still remain almost the same as those in the Isgur-Karl model and are smaller than the data, and the estimated value for the $E2/M1$ ratio is about a factor two smaller in comparison with the new data [11,32,33], although it agrees with the data of the Particle Data Group. These discrepancies mean the limitations of the present chiral constituent quark model, where the meson cloud effect is approximately reflected in the Goldstone bosons exchange interaction between the constituent quarks for simplicity. To solve the problems, we believe that the consideration of the dynamical model of pion photoproduction and electroproduction given by Nozawa, Blankleider, and Lee [40] is hopeful.

Actually, the present chiral quark model is just one way to improve the theoretical predictions for the $E2/M1$ and $C2/M1$ ratios of $\Delta(1232)$. The constituent quark model calculation based on the consideration of the two-body exchange currents by Buchmann, Hernandez, and Faessler [41] is another method to enhance the predicted value of the ratio $E2/M1$. However, the two-body currents play a negative role to the photocouplings [42]. In addition, it should be mentioned that the spectroscopy of $P_{11}(1440)$ and $P_{33}(1600)$ in the Isgur-Karl model are more than 100 MeV heavier than the experimental data. Therefore, the spectroscopy of the two states is perhaps the most problematic in both nonrelativistic and relativistic versions of the Isgur-Karl model. The calculation of photoproduction and electroproduction by Li, Burkert, and Li [43] indicated that both resonances might be hybrid states other than three-quark excited states. The identification of the two states is still an open issue. We believe that the future experiments at Jefferson Lab would provide us hints about their structures.

To summarize this paper, we have show the remarkable effect of the relativistic corrections in the electromagnetic transition operators on the determination of the $\Delta(1232)$ properties. The important role of the chiral meson cloud is also confirmed. We conclude that all the relativistic effects embodied both in the transition operators and in the configuration mixing caused by the tensor force of the chiral meson exchange interaction should be considered simultaneously.

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