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รายงานการวิจัย

ผลของความแปลกต่อฟอร์มแฟกเตอร์เชิงแกนของนิวคลีออน

(Strangeness contribution to axial form factors of nucleon)

ได้รับทุนอุดหนุนการวิจัยจาก

มหาวิทยาลัยเทคโนโลยีสุรนารี

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Strangeness Contribution to Axial Form Factors of Nucleon

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บทคัดย่อ

ในโครงการวิจัยนี้ ฟอร์มแฟกเตอร์เชิงแกนและประจุเชิงแกนของบาริออนชุดแปดได้ถูกศึกษาโดยใช้แบบจำลองควาร์กเชิงไคแรลเพอร์เทอร์เบชันด้วยฟังก์ชันคลื่นของควาร์กที่ถูกกำหนดไว้ล่วงหน้า โดยที่ฟังก์ชันคลื่นของควาร์กเชิงสัมพัทธภาพสามารถคำนวณได้จากการเทียบผลที่ได้เชิงทฤษฎีของฟอร์มแฟกเตอร์เชิงประจุของโปรตอนเทียบกับผลการทดลอง จากการศึกษาวิจัยครั้งนี้ พบว่าผลการคำนวณเชิงทฤษฎีของฟอร์มแฟกเตอร์และประจุเชิงแกนสอดคล้องเป็นอย่างดีกับข้อมูลที่ได้จากการทดลองและผลการคำนวณของแลตทิซคิวซีดี นอกจากนี้ยังพบว่ากลุ่มหมอกของมีซอนมีบทบาทสำคัญต่อประจุเชิงแกนของบาริออนชุดแปดโดยมีผลกระทบ 30 – 40 % ของค่าที่ได้ทั้งหมด และทะเลของควาร์กชนิดเอสยังมีความสำคัญต่อประจุเชิงแกนของบาริออนประเภท Σ และ Ξ

ABSTRACT IN ENGLISH

The axial form factor as well as the axial charge of octet baryons are studied in the perturbative chiral quark model (PCQM) with the predetermined quark wave functions, in which the relativistic quark wave functions are extracted by fitting the theoretical results of the proton charge form factor to the experimental data. It is found that the theoretical results of the axial form factors and axial charges agree well with experimental data and lattice-QCD values. The meson cloud plays an important role in the axial charge of octet baryons, contributing 30%-40% to the total values, and strange sea quarks have a considerable contribution to the axial charge of the Σ and Ξ.

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Chapter 1

Introduction

The nucleon axial form factor is of fundamental significance to weak interaction properties and to the pion-nucleon interaction. Hence it provides one important test for theories that attempt to describe the structure of the nucleon. In recent year, the Q^2-dependence of the nucleon axial form factor has been studied in Lattice-QCD [1, 2] and chiral perturbation theory [3] and other approaches [4, 5], in which the theoretical results are in good agreement with experimental data. The theoretical and experimental understanding of the axial structure of nucleon at low energy have been reviewed in Ref. [6]. The axial charges of hyperons, which are the axial form factors in zero-recoil, have been predicted in chiral perturbation theory [7, 8], relativistic constituent quark model (RCQM) [9] and Lattice-QCD [10, 11]. However, there is few theoretical works on the Q^2-dependence of the axial form factor of hyperons, especially in the chiral quark model. This inspires us to study the axial form factors of octet baryons in the perturbative chiral quark model (PCQM). In this work, we attempt to study the axial form factors of octet baryons in the PCQM with the determined wave functions [12] and seriously analysize the strangeness contributions to the axial form factors.

Chapter 2

Perturbative chiral quark model (PCQM)

The PCQM [12–22] is based on an effective chiral Lagrangian describing baryons by a core of the three valence quarks, moving in a central Dirac field with $V_{\rm eff}(r) = S(r) + \gamma_0 V(r)$, where $r = |\vec{x}|$. In order to respect chiral symmetry, a cloud of Goldstone bosons (π, K and η) is included as small fluctuations around the three-quark core in SU(3) extension. With an unitary chiral rotation, as shown in Refs. [15, 19], the Weinberg-type Lagrangian of the PCQM is derived,

$$\begin{aligned}
\mathcal{L}^W(x) &= \mathcal{L}_0(x) + \mathcal{L}_I^W(x) + o(\vec{\pi}), && (2.1)\\
\mathcal{L}_0(x) &= \bar{\psi}(x)\big[i\partial\!\!\!/ - \gamma^0 V(r) - S(r)\big]\psi(x) - \frac{1}{2}\Phi_i(x)\big(\Box + M_\Phi^2\big)\Phi^i(x), && (2.2)\\
\mathcal{L}_I^W(x) &= \frac{1}{2F}\partial_\mu\Phi_i(x)\bar{\psi}(x)\gamma^\mu\gamma^5\lambda^i\psi(x) + \frac{f_{ijk}}{4F^2}\Phi_i(x)\partial_\mu\Phi_j(x)\bar{\psi}(x)\gamma^\mu\lambda_k\psi(x), && (2.3)
\end{aligned}$$

where f_{ijk} are the totally antisymmetric structure constant of $SU(3)$, the pion decay constant $F = 88$ MeV in the chiral limit, Φ_i are the octet meson fields, and $\psi(x)$ is the triplet of the u, d, and s quark fields taking the form

$$\psi(x) = \begin{pmatrix} u(x) \\ d(x) \\ s(x) \end{pmatrix}. \qquad (2.4)$$

The quark field $\psi(x)$ could be expanded in

$$\psi(x) = \sum_{\alpha} \left(b_\alpha u_\alpha(\vec{x})\, e^{-i\mathcal{E}_\alpha t} + d_\alpha^\dagger \upsilon_\alpha(\vec{x}) e^{i\mathcal{E}_\alpha t} \right), \tag{2.5}$$

where b_α and $d_\alpha^\dagger$ are the single quark annihilation and antiquark creation operators. The ground state quark wave function $u_0(\vec{x})$ may, in general, be expressed as

$$u_0(\vec{x}) = \begin{pmatrix} g(r) \\ i\vec{\sigma}\cdot\hat{x} f(r) \end{pmatrix} \chi_s \chi_f \chi_c, \tag{2.6}$$

where χ_s, χ_f and χ_c are the spin, flavor and color quark wave functions, respectively. The previous work [19] on axial form factor of nucleon has been studied in the PCQM employed Gaussian-type wave functions. As we argue in Ref. [12], the Gaussian-type quark wave functions of baryons lead to the theoretical predictions for the form factors of baryons consistent with experimental data only at very low momentum transfer Q^2. In the numerical analysis, instead, we employ the radial quark wave functions $g(r)$ and $f(r)$ as shown in Fig. 2.1 which have been extracted in Ref. [12] by fitting the theoretical results of the proton charge form factor to the experimental data. More information on quark wave functions can be found in Ref. [12].

The calculation technique in the PCQM is based on the Gell-Mann and Low theorem [23], in which the expectation value of an operator $\hat{O}$ can be calculated from

$$\langle \hat{O} \rangle = {}^B\langle \phi_0 | \sum_{n=0}^{\infty} \frac{i^n}{n!} \int d^4x_1 \cdots \int d^4x_n T[\mathcal{L}_I^W(x_1) \cdots \mathcal{L}_I^W(x_n) \hat{O}] | \phi_0 \rangle_c^B, \tag{2.7}$$

where the state vector $|\phi_0\rangle^B$ corresponds to the unperturbed three-quark states projected onto the respective baryon states, which are constructed in the framework of the $SU(6)$ spin-flavor and $SU(3)$ color symmetry. The subscript c in Eq. (2.7) refers to contributions from connected graphs only. $\mathcal{L}_I^W(x)$ is the quark-meson interaction Lagrangian as given in Eq. (2.3).

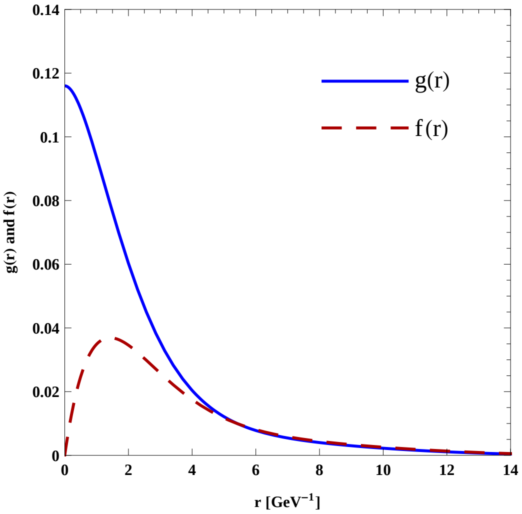

Figure 2.1: Normalized radial wave functions of the valence quarks for the upper component $g(r)$ and the lower component $f(r)$ with the central values of the expansion coefficients, which are determined by fitting the theoretical results of proton charge form factor to the experimental data [12].

Chapter 3

Axial form factors in the PCQM

In the framework of the PCQM, the axial form factors $G_A^B(Q^2)$ of octet baryons in the Breit frame are defined by

$$\begin{aligned}\chi^\dagger_{B_{s'}}\frac{\vec{\sigma}_B}{2}\chi_{B_s}G_A^B(Q^2) &= {}^B\langle\phi_0|\sum_{n=0}^{2}\frac{\mathrm{i}^n}{n!}\int\delta(t)d^4xd^4x_1\cdots d^4x_ne^{-\mathrm{i}q\cdot x}\\ &\times T[\mathcal{L}_I^W(x_1)\cdots\mathcal{L}_I^W(x_n)\vec{A}_3(x)]|\phi_0\rangle_c^B, \end{aligned}\tag{3.1}$$

χ_{B_s} and $\chi^\dagger_{B_{s'}}$ are the baryon spin wave functions in the initial and final states, $\vec{\sigma}_B$ is the baryon spin matrix. $G_A^B(Q^2)$ are the axial form factors of octet baryons with the squared momentum transfer Q^2.

The axial-vector current A_i^μ in Eq. (3.1) is given by

$$A_i^\mu = F\partial^\mu\Phi_i+\bar{\psi}\gamma^\mu\gamma^5\frac{\lambda_i}{2}\psi-\frac{f_{ijk}}{2F}\bar{\psi}\gamma^\mu\lambda_j\psi\Phi_k+\bar{\psi}(\hat{Z}-1)\gamma^\mu\gamma^5\frac{\lambda_i}{2}\psi+o(\Phi_i^2)\tag{3.2}$$

where the renormalization constants $\hat{Z}$ is determined by the nucleon charge conservation condition as

$$\hat{Z} = 1-\frac{3}{4(2\pi F)^2}\int_0^\infty dkk^4F_I^2(k^2)\Big[\frac{1}{\omega_\pi^3(k^2)}+\frac{2}{3\omega_K^3(k^2)}+\frac{1}{9\omega_\eta^3(k^2)}\Big],\tag{3.3}$$

with $\omega_\Phi(k^2)=\sqrt{M_\Phi^2+k^2}$ and the vertex function $F_I(k)$ for the $qq\Phi$ system taking

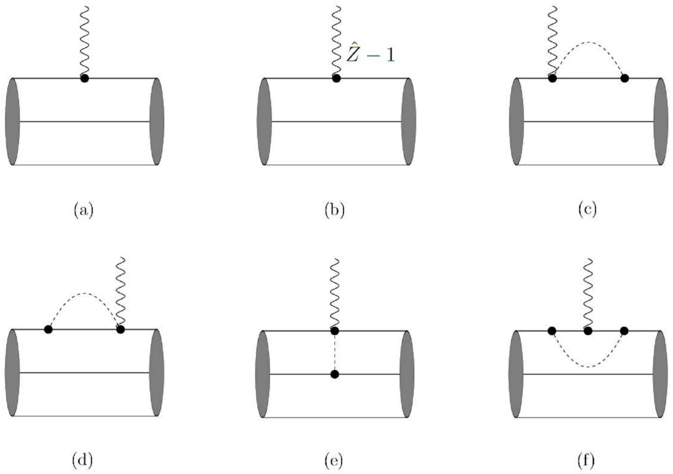

Figure 3.1: Diagrams contributing to the axial form factor of octet baryons : 3q-core leading order (a), 3q-core counterterm (b), self-energy I (c) self-energy II (d), meson exchange (e), and vertex correction (f).

the form

$$F_I(k) \quad = \quad 2\pi \int_0^\infty drr^2 \int_0^\pi d\theta \sin\theta e^{ikr\cos\theta}[g(r)^2 + f(r)^2 \cos 2\theta]. \tag{3.4}$$

In accordance with the interaction Lagrangian $\mathcal{L}_I^W(x)$ in Eq. (2.3) and the axial current A^μ in Eq. (3.2), there are six Feynman diagrams, as shown in Figure 3.1, contributing to the axial form factors to the one-loop order. The contributions of these diagrams are derived as follows:

(a) Three-quark core leading-order (LO) diagram

$$G_A^B(Q^2)\big|_{LO} \quad = \quad c_1^B 2\pi \int_0^\infty drr^2 \int_0^\pi d\theta \sin\theta e^{iQr\cos\theta}[g(r)^2 + f(r)^2 \cos(2\theta)]. \tag{3.5}$$

(b) Three-quark core counterterm (CT) diagram

$$G_A^B(Q^2)\big|_{CT} = (\hat{Z} - 1) G_A^B(Q^2)\big|_{LO}. \tag{3.6}$$

Table 3.1: The constants c_i^B for the octet baryons axial form factors $G_A^B(Q^2)$.

	c_1	c_2	c_3	c_4	c_5
N	$5/3$	$5/6$	8	0	$-5/9$
Σ	$4/3$	$2/3$	0	4	$-4/9$
Ξ	$-1/3$	$-1/6$	0	-4	$1/9$

(c) Self-energy I (SE:I) diagram

$$\begin{aligned} G_A^B(Q^2)\big|_{SE:I} &= \frac{1}{2(2\pi F)^2}\int_0^\infty dk k^4 \int_{-1}^{1} dx(1-x^2) \\ &\quad \times \frac{F_I(k)F_{II}(k_-)}{\sqrt{k_-^2}}\left[\frac{c_1^B}{\omega_\pi^2(k^2)}+\frac{c_2^B}{\omega_K^2(k^2)}\right]. \end{aligned} \tag{3.7}$$

where $k_- = \sqrt{k^2+Q^2-2k\sqrt{Q^2}x}$, and the vertex function for the quark-pion-axial vector current $F_{II}(k)$ is given by

$$F_{II}(k) = -2i\pi\int_0^\infty dr r^2\int_0^\pi d\theta g(r)f(r)\sin 2\theta e^{ikr\cos\theta}. \tag{3.8}$$

(d) Self-energy II (SE:II) diagram

$$\begin{aligned} G_A^B(Q^2)\big|_{SE:II} &= \frac{1}{2(2\pi F)^2}\int_0^\infty dk k^4 \int_{-1}^{1} dx(1-x^2) \\ &\quad \times \frac{F_I(k)F_{II}(k_-)}{\sqrt{k_-^2}}\left[\frac{c_1^B}{\omega_\pi^2(k^2)}+\frac{c_2^B}{\omega_K^2(k^2)}\right]. \end{aligned} \tag{3.9}$$

(e) Exchange (EX) diagram

$$\begin{aligned} G_A^B(Q^2)\big|_{EX} &= \frac{1}{4(2\pi F)^2}\int_0^\infty dk k^4 \int_{-1}^{1} dx(1-x^2) \\ &\quad \times \frac{F_I(k)F_{II}(k_-)}{\sqrt{k_-^2}}\left[\frac{c_3^B}{\omega_\pi^2(k^2)}+\frac{c_4^B}{\omega_K^2(k^2)}\right]. \end{aligned} \tag{3.10}$$

(f) Vertex-correction (VC) diagram

$$G_A^B(Q^2)\big|_{VC} = \frac{1}{20(2\pi F)^2}\int_0^\infty dk k^4 F_I^2(k)\left[\frac{c_1^B}{\omega_\pi^3(k^2)}+\frac{c_5^B}{\omega_\eta^3(k^2)}\right]\cdot G_A^N(Q^2)\big|_{LO} \tag{3.11}$$

The constants c_i^B are given in Table 3.1.

Chapter 4

Strangeness contribution to axial form factors

The numerical results listed in Table 4.1 are the axial charges, namely the axial form factors in zero-recoil. The uncertainties in the total values of the axial charges caused by the fitting errors of the quark wave functions [12] are estimated about 15%. As shown in Table 4.1, the theoretical results reveal that the meson cloud plays an important role in the axial charge of octet baryons, contributing 30%-40% to the total values. Except for the N, there is no direct experimental data for the axial charge of the Σ and Ξ, thus we also compile the chiral extrapolation estimations of Lattice-QCD results at the physical m_π point [10] in the last second column of table for comparison. It is found that the theoretical N axial charge is in good agreement with the experimental value [24], and the work predictions on Σ and Ξ axial charges are consistent with the Lattice-QCD values [10].

Table 4.1: Numerical results for the octet baryon axial charges g_A^B, where the uncertainties are from the errors of the quark wave functions. The experimental data are taken from [24], while the chiral extrapolation estimations of Lattice-QCD results at the physical m_π point are taken from [10].

	3q LO	Meson loops CT+SE+EX+VC	Total	Lattice [10]	Exp. [24]
g_A^N	0.883	0.418	1.301 ± 0.230	1.180 ± 0.100	1.272 ± 0.002
g_A^Σ	0.707	0.220	0.927 ± 0.132	0.900 ± 0.096	—
g_A^Ξ	-0.177	-0.106	-0.283 ± 0.033	-0.277 ± 0.034	—

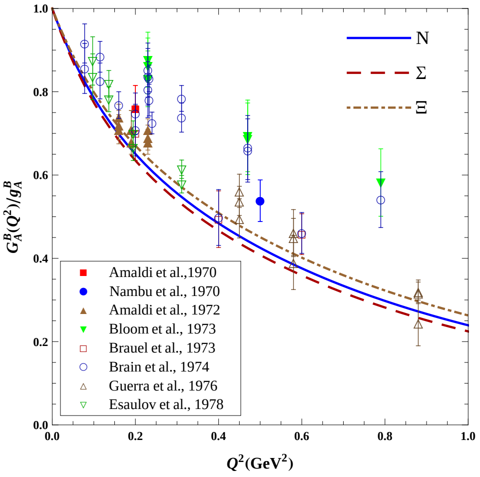

Figure 4.1: Normalized axial form factors $G_A^B(Q^2)/g_A^B$ of octet baryons. The experimental data on nucleon axial form factor are taken from [25–32].

Table 4.2: Contribution of π, K and η mesons to the axial charges g_A^B.

	Meson loops		
	π	K	η
g_A^N	0.375	0.045	-0.002
g_A^Σ	0.118	0.104	-0.002
g_A^Ξ	-0.030	-0.077	-0.001

We show the Q^2-dependence of the axial form factors of octet baryons in Fig. 4.1, which are normalized to one at zero-recoil, with the experimental data on the nucleon axial form factor [25–32] plotted as well. As expected, the theoretical axial form factors fall off smoothly as the momentum transfer Q^2 increases. It is also found that the theoretical result for the N axial form factor is in good agreement with the experimental data [25–32], and the axial form factors for Σ and Ξ show a similar Q^2-dependence based on the SU(3) symmetry.

We also present in Fig. 4.2 the individual contributions of various processes shown in Fig. 3.1 to the axial form factors of octet baryons. As shown in Fig. 4.2, the 3q-core leading order (LO) diagram dominates the axial form factors of octet baryons while the self-energy (SE) and exchange (EX) diagrams contribute considerably.

To investigate the strangeness effects, we separately list the π, K and η mesons contributions to the axial charges in Table 4.2. It is found that the π meson contribution to the N axial charge dominates over the ones from the K and η mesons, but the K meson contributions to the Σ and Ξ axial charges are in the same order as the π ones. The contribution from the η meson is negligible due to the weak coupling between the s current quark and η meson. We also present in Table 4.3 the strange sea quark contributions (K and η meson clouds) of the individual loop diagrams as shown in Fig. 3.1 to the axial charges g_A^B. Based on Eqs. (3.5)-(3.11), we may point out the fact that the K meson contributes to the SE and EX diagrams while the η meson participates in the VC process only. The results listed in Table 4.3 reveal that the strange sea quark contribution to the N axial charge is caused mainly by the SE diagram, but to the Σ and Ξ axial charges both the SE and EX diagrams

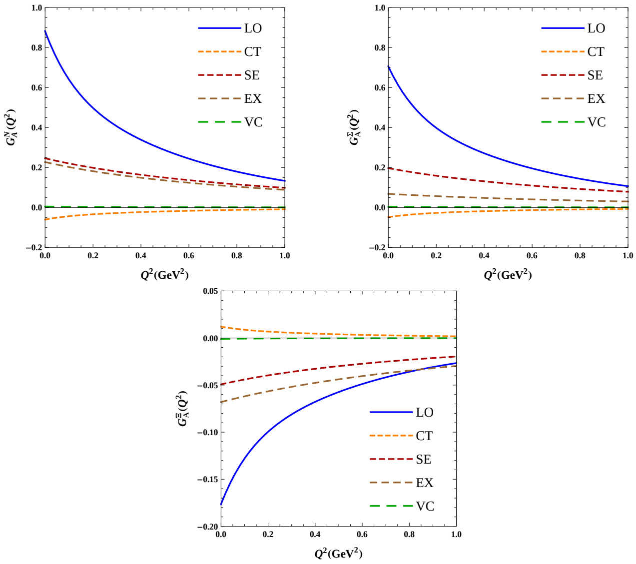

Figure 4.2: The individual contributions of the different diagrams of Fig. 3.1 to the axial form factors of octet baryons (left panel for N, middle panel for Σ and right panel for Ξ).

Table 4.3: Strange sea quark contributions of the individual loop diagrams of Fig. 3.1 to the axial charges g_A^B.

	CT	SE	EX	VC
g_A^N	−0.0136	0.0567	0	−0.0006
g_A^Σ	−0.0109	0.0453	0.0680	−0.0004
g_A^Ξ	0.0027	−0.0113	−0.0680	0.0001

Table 4.4: Numerical results for the octet baryon axial radii $\left\langle r_A^2 \right\rangle_B^{1/2}$ (in units of fm), where the uncertainties are from the errors of the quark wave functions. The experimental data are taken from Ref.[6].

	PCQM	Data[6]
$\left\langle r_A^2 \right\rangle_N^{1/2}$	0.808 ± 0.088	0.639 ± 0.010
$\left\langle r_A^2 \right\rangle_\Sigma^{1/2}$	0.832 ± 0.089	...
$\left\langle r_A^2 \right\rangle_\Xi^{1/2}$	0.780 ± 0.087	...

are important. As shown in the last column of Table 4.3, the η meson contribution is suppressed owing to the weak coupling between the s current quark and η meson.

Listed in Table 4.4 are the axial radii of octet baryons, which are derived by

$$\left\langle r_A^2 \right\rangle_B = -6 \frac{1}{g_A^B} \frac{dG_A^B(Q^2)}{dQ^2}\bigg|_{Q^2=0} \tag{4.1}$$

The nucleon axial radius $\left\langle r_A^2 \right\rangle_N^{1/2}$ in the Table 4.4 is a little bit larger than the experimental value, and the predicted results for the $\left\langle r_A^2 \right\rangle_\Sigma^{1/2}$ and $\left\langle r_A^2 \right\rangle_\Xi^{1/2}$ are in the same order as $\left\langle r_A^2 \right\rangle_N^{1/2}$ since our calculations are restricted to the SU(3) chiral symmetry.

In summary, one may conclude that the theoretical results of the axial form factors and axial charges agree well with experimental data and lattice-QCD values. The meson cloud plays an important role in the axial charge of octet baryons, contributing 30%-40% to the total values, and strange sea quarks have a considerable contribution to the axial charge of the Σ and Ξ.

Bibliography

[1] K. F. Liu, S. J. Dong, T. Draper, J. M. Wu, and W. Wilcox. *Phys. Rev. D*, 49:4755, 1994.

[2] C. Alexandrou, M. Brinet, J. Carbonell, M. Constantinou, P. A. Harraud, P. Guichon, K. Jansen, T. Korzec, and M. Papinutto. *Phys. Rev. D*, 83:045010, 2011.

[3] M. R. Schindler and S. Scherer. *Eur. Phys. J. A*, 32:429, 2007.

[4] G. Erkol and A. Ozpineci. *Phys. Rev. D*, 83:114022, 2011.

[5] G. Eichmann and C. S. Fischer. *Eur. Phys. J. A*, 48:1434, 2012.

[6] V. Bernard, L. Elouadrhiri, and U. G. Meißner. *J. Phys. G: Nucl. Part. Phys.*, 28:R1, 2002.

[7] F. J. Jiang and B. C. Tiburzi. *Phys. Rev. D*, 78:017504, 2008.

[8] F. J. Jiang and B. C. Tiburzi. *Phys. Rev. D*, 80:077501, 2009.

[9] K. S. Choi, W. Plessas, and R. F. Wagenbrunn. *Phys. Rev. D*, 82:014007, 2010.

[10] H. W. Lin and K. Orginos. *Phys. Rev. D*, 79:034507, 2009.

[11] G. Erkol, M. Oka, and T. T. Takahashi. *Phys. Lett. B*, 686:36, 2010.

[12] X. Y. Liu, K. Khosonthongkee, A. Limphirat, and Y. Yan. *J. Phys. G: Nucl. Part. Phys.*, 41:055008, 2014.

[13] V. E. Lyubovitskij, Th. Gutsche, A. Faessler, and E. G. Drukarev. *Phys. Rev. D*, 63:054026, 2001.

[14] V. E. Lyubovitskij, Th. Gutsche, and A. Faessler. *Phys. Rev. C*, 64:065203, 2001.

[15] V. E. Lyubovitskij, Th. Gutsche, A. Faessler, and M. R. Vinh. *Phys. Lett. B*, 520:204, 2002.

[16] V. E. Lyubovitskij, Th. Gutsche, Amand Faessler, and R. Vinh Mau. *Phys. Rev. C*, 65:025202, 2002.

[17] K. Pumsa-ard, V. E. Lyubovitskij, Th. Gutsche, A. Faessler, and S. Cheedket. *Phys. Rev. C*, 68:015205, 2003.

[18] S. Cheedket, V. E. Lyubovitskij, Th. Gutsche, A. Faessler, K. Pumsa-ard, and Y. Yan. *Eur. Phys. J. A*, 20:317, 2004.

[19] K. Khosonthongkee, V. E. Lyubovitskij, Th. Gutsche, A. Faessler, K. Pumsa-ard, S. Cheedket, and Y. Yan. *J. Phys. G: Nucl. Part. Phys.*, 30:793, 2004.

[20] Y. Dong, A. Faessler, Th. Gutsche, J. Kuckei, V. E. Lyubovitskij, K. Pumsa-ard, and P. Shen. *J. Phys. G: Nucl. Part. Phys.*, 32:203, 2006.

[21] C. Dib, A. Faessler, Th. Gutsche, S. Kovalenko, J. Kuckei, V. E. Lyubovitskij, and K. Pumsa-ard. *J. Phys. G: Nucl. Part. Phys.*, 32:547, 2006.

[22] A. Faessler, Th. Gutsche, V. E. Lyubovitskij, and C. Oonariya. *J. Phys. G: Nucl. Part. Phys.*, 35:025005, 2008.

[23] G. Murray and L. Francis. *Phys. Rev.*, 84:350, 1951.

[24] K. A. Olive et al. *Chin. Phys. C*, 38:090001, 2014.

[25] E. Amaldi et al. *Nuovo Cimento A*, 65:377, 1970.

[26] Y. Nambu and M. Yoshimura. *Phys. Rev. Lett.*, 24:25, 1970.

[27] E. Amaldi et al. *Phys. Lett. B*, 41:213, 1972.

[28] E. D. Bloom et al. *Phys. Rev. Lett.*, 30:1186, 1973.

[29] P. Brauel et al. *Phys. Lett. B*, 45:389, 1973.

[30] B. J. Read et al. *Nucl. Phys. B*, 74:482, 1974.

[31] A. D. Guerra et al. *Nucl. Phys. B*, 107:65, 1976.

[32] A. S. Esaulov, A. M. Pilipenko, and Y. I. Titov. *Nucl. Phys. B*, 136:511, 1978.

Appendices

Appendix A

Gell-Mann and Low theorem

The Gell-Mann and Low theorem was proved by Murray Gell-Mann and Francis E. Low in 1951. It is a theorem in quantum field theory that allows one to relate the ground (or vacuum) state of an interacting system to the ground state of the corresponding non-interacting theory. We consider a system described by the Hamiltonian H which might be written as

$$H = H_0 + H_I \tag{A.1}$$

where H_0 and H_I are respectively the free and interaction parts of the Hamiltonian. Let $|\psi_0\rangle$ and $|n\rangle$ be the eigenstates of the free and full Hamiltonian, respectively. One has

$$\begin{aligned} H|n\rangle &= E^{(n)}|n\rangle, \\ H_0|\psi_0\rangle &= E_0|\psi_0\rangle, \end{aligned} \tag{A.2}$$

hence

$$\begin{aligned} e^{-\mathrm{i}Ht}|\psi_0\rangle &= \sum_n e^{-\mathrm{i}E^{(n)}t}|n\rangle\langle n|\psi_0\rangle \\ &= e^{-\mathrm{i}Et}|\psi\rangle\langle\psi|\psi_0\rangle + \sum_{n\neq 0} e^{-\mathrm{i}E^{(n)}t}|n\rangle\langle n|\psi_0\rangle, \end{aligned} \tag{A.3}$$

here we have rewritten ground eigenstate $|0\rangle$ and ground eigenvalue $E^{(0)}$ in the above equation respectively as $|\psi\rangle$ and E, that is

$$H|\psi\rangle = E|\psi\rangle. \tag{A.4}$$

Multiplying the above equation by $e^{\mathrm{i}E_0 t}$, one derives

$$e^{\mathrm{i}E_0 t}e^{\mathrm{i}Ht}|\psi_0\rangle = e^{\mathrm{i}(E-E_0)t}|\psi\rangle\langle\psi|\psi_0\rangle + \sum_{n\neq 0} e^{-\mathrm{i}(E^{(n)}-E_0)t}|n\rangle\langle n|\psi_0\rangle. \tag{A.5}$$

Since $E^{(n)} > E$ for all $n \neq 0$, we can get rid of all the $n \neq 0$ terms in the series by sending t to ∞ in a slightly imaginary direction $t \to \infty(1-\mathrm{i}\varepsilon)$. Then the exponential factor $e^{-\mathrm{i}(E-E_0)t}$ dies slowest and we have

$$\begin{aligned} |\psi\rangle &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{e^{\mathrm{i}H(-t)}e^{-\mathrm{i}H_0(-t)}|\psi_0\rangle}{e^{-\mathrm{i}(E-E_0)t}\langle\psi|\psi_0\rangle} \\ &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{U(0,-t)|\psi_0\rangle}{e^{-\mathrm{i}(E-E_0)t}\langle\psi|\psi_0\rangle}. \end{aligned} \tag{A.6}$$

here we have used

$$U(t_0, t) = e^{\mathrm{i}H(t-t_0)}e^{-\mathrm{i}H_0(t-t_0)}. \tag{A.7}$$

In the same way, we can derive

$$\langle\psi| = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,0)}{e^{-\mathrm{i}(E-E_0)t}\langle\psi_0|\psi\rangle}. \tag{A.8}$$

Now we evaluate the expectation value of the operator $O(x) \equiv O(x^0, \vec{x})$ in the state $|\psi\rangle$

$$\begin{aligned} \langle\psi|O(x^0,\vec{x})|\psi\rangle &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,0)U^\dagger(x^0,0)O_I(x)U(x^0,0)U(0,-t)|\psi_0\rangle}{e^{-\mathrm{i}(E-E_0)t}\langle\psi_0|\psi\rangle e^{-\mathrm{i}(E-E_0)t}\langle\psi|\psi_0\rangle} \\ &= \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,x^0)O_I(x)U(x^0,-t)|\psi_0\rangle}{e^{-2\mathrm{i}(E-E_0)t}|\langle\psi_0|\psi\rangle|^2}. \end{aligned} \tag{A.9}$$

To get rid of the denominator in the equation, one may divide it by 1 in the form

$$1 = \langle\psi|\psi\rangle = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,0)U(0,-t)|\psi_0\rangle}{e^{-2\mathrm{i}(E-E_0)t}|\langle\psi_0|\psi\rangle|^2}. \tag{A.10}$$

Then finally we derive

$$\langle\psi|O(x^0,\vec{x})|\psi\rangle = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|U(t,x^0)O_I(x)U(x^0,-t)|\psi_0\rangle}{\langle\psi_0|U(t,-t)|\psi_0\rangle}. \tag{A.11}$$

The above equation holds for a product of arbitrarily many operators, for example, for two operators

$$\langle\psi|T[O(x)P(x)]|\psi\rangle = \lim_{t\to\infty(1-\mathrm{i}\varepsilon)} \frac{\langle\psi_0|T\{O_I(x)P_I(x)\exp[-\mathrm{i}\int_{-t}^{t} dz H_I(z)]\}|\psi_0\rangle}{\langle\psi_0|T\{\exp[-\mathrm{i}\int_{-t}^{t} dz H_I(z)]\}|\psi_0\rangle}. \tag{A.12}$$

Appendix B

Calculation of the diagrams for the axial form factor

In the PCQM, the axial form factor of the baryon octet is given by

$$\begin{aligned}\chi^{\dagger}_{B_{s'}}\vec{\sigma}_B\frac{\tau^3_B}{2}\chi_{B_s}G^B_A(Q^2) &= {}^B\langle\phi_0|\sum_{n=0}^{2}\frac{i^n}{n!}\int\delta(t)d^4xd^4x_1\cdots d^4x_n\mathrm{e}^{-\mathrm{i}qx} \\ &\quad\times T[\mathcal{L}^W_I(x_1)\cdots\mathcal{L}^W_I(x_n)\vec{A}_3(x)]|\phi_0\rangle^B_c,\end{aligned} \tag{B.1}$$

where χ_{B_s} and $\chi^{\dagger}_{B_{s'}}$ are the baryon spin wavefunctions in the initial and final states, $\vec{\sigma}$ is the spin matrix and τ_3 is the third component of the SU(2) isospin matrix. On the baryon level

$$\chi^{\dagger}_{B_{s'}}\vec{\sigma}_B\frac{\tau^3_B}{2}\chi_{B_s}=\frac{1}{2}. \tag{B.2}$$

B.1 Leading Order Diagram (LO)

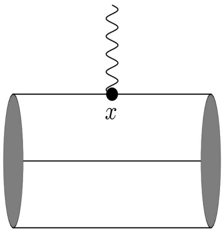

Figure B.1: Leading order diagram

$$
\begin{aligned}
&G_A^B(Q^2)\big|_{LO} \\
&= 2\,{}^B\langle\phi_0|\int\delta(x)d^4xe^{iqx}\bar{\psi}(x)\gamma^3\gamma^5\frac{\lambda_3}{2}\psi(x)|\phi_0\rangle^B \\
&= {}^B\langle\phi_0|b_0^\dagger\int d^3xe^{\mathrm{i}\vec{q}\cdot\vec{x}}u_0^\dagger(x)\gamma^0\gamma^3\gamma^5\lambda_3u_0(x)b_0|\phi_0\rangle^B \\
&= 2\pi\int_0^\infty dr\int_0^\pi d\theta r^2\mathrm{sin}\theta[g(r)^2+f(r)^2\mathrm{cos}(2\theta)]e^{\mathrm{i}Qr\mathrm{cos}\theta} \\
&\quad\times{}^B\langle\phi_0|b_0^\dagger\chi_{c'}^\dagger\chi_{f'}^\dagger\chi_{s'}^\dagger(\sigma_3\lambda_3)\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B \\
&= c_1^B2\pi\int_0^\infty dr\int_0^\pi d\theta r^2\mathrm{sin}\theta[g(r)^2+f(r)^2\mathrm{cos}(2\theta)]e^{\mathrm{i}Qr\mathrm{cos}\theta} \qquad \text{(B.3)}
\end{aligned}
$$

where

$$
\begin{aligned}
c_1^B &= \langle\phi_0|b_0^\dagger\chi_{c'}^\dagger\chi_{f'}^\dagger\chi_{s'}^\dagger(\sigma_3\lambda_3)\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B \\
&= {}^B\langle B\uparrow|\sum_{k=1}^{3}[\sigma_3\lambda_3]^{(k)}|B\uparrow\rangle. \qquad \text{(B.4)}
\end{aligned}
$$

B.2 Counterterm Diagram (CT)

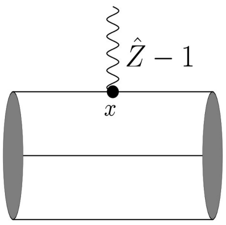

Figure B.2: Counterterm diagram

$$
\begin{aligned}
&G_A^B(Q^2)\big|_{CT} \\
&= 2\,{}^B\langle\phi_0|\int\delta(x)d^4xe^{iqx}\bar{\psi}(x)(\hat{Z}-1)\gamma^3\gamma^5\frac{\lambda_3}{2}\psi(x)|\phi_0\rangle^B \\
&= (\hat{Z}-1)G_A^B(Q^2)\big|_{LO}. \qquad \text{(B.5)}
\end{aligned}
$$

B.3 Self-Energy Diagram I (SE;I)

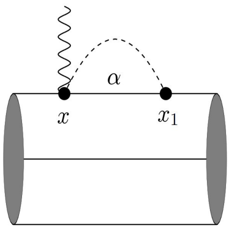

Figure B.3: Self-energy diagram I

$$
\begin{aligned}
&G_A^B(Q^2)\big|^{\alpha}_{SE;I}\\
&= 2\,{}^B\langle\phi_0|i\int\delta(t)d^4xd^4x_1e^{-\mathrm{i}qx}\\
&\quad\times N\Big\{\Big[\frac{1}{2F}\partial_\mu\Phi_m\bar{\psi}\gamma^\mu\gamma^5\lambda_m\psi\Big]_{x_1}\Big[-\frac{f_{3ij}}{2F}\bar{\psi}\gamma^3\lambda_i\psi\Phi_j\Big]_x\Big\}|\phi_0\rangle^B\\
&= \frac{2if_{3ij}}{4F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3xd^3x_1d^4ke^{i\vec{q}\cdot\vec{x}}\frac{e^{i\vec{k}\cdot(\vec{x}_1-\vec{x})}}{M_\Phi^2-k^2-i\epsilon}\\
&\quad\times\bar{u}_0(x_1)\gamma^\mu k_\mu\gamma^5\lambda_ju_\alpha(x_1)\bar{u}_\alpha(x)\gamma^3\lambda_iu_0(x)\\
&\quad\times\int dtdt_1\delta t\Theta(t_1-t)e^{-iq_0t}e^{-i\varepsilon_0(t-t_1)}e^{-i\varepsilon_\alpha(t_1-t)}e^{-ik^0(t_1-t)}b_0|\phi_0\rangle^B\\
&= \frac{f_{3ij}}{2F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3xd^3x_1d^3ke^{i\vec{q}\cdot\vec{x}}e^{i\vec{k}\cdot(\vec{x}_1-\vec{x})}\\
&\quad\times\int dk_0\frac{1}{[\omega_\Phi(k^2)-k_0^2+i\epsilon][\Delta\varepsilon_\alpha+k_0-i\eta]}\\
&\quad\times\bar{u}_0(x_1)(\gamma^0k_0-\vec{\gamma}\cdot\vec{k})\gamma^5\lambda_ju_\alpha(x_1)\bar{u}_\alpha(x)\gamma^3\lambda_iu_0(x)b_0|\phi_0\rangle^B\\
&= \frac{i}{4F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\int d^3k\frac{f_{3ij}}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]}\\
&\quad\times\big[\omega_\Phi(k^2)F_{I\alpha}(k)-F_{II\alpha}(k)\big][(\vec{\sigma}\cdot\vec{k})\lambda_j]_{0,\alpha}\Big\{\frac{F_{III\alpha}(|\vec{q}-\vec{k}|)}{|\vec{q}-\vec{k}|}[\epsilon_{3mn}k_m\sigma_n\lambda_i]_{\alpha,0}\\
&\quad+\frac{F_{IV\alpha}(|\vec{q}-\vec{k}|)}{|\vec{q}-\vec{k}|}[\sqrt{Q^2}-k_3+i\epsilon_{3mn}\sigma_mk_n\lambda_i]_{\alpha,0}\Big\}\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B, \qquad \text{(B.6)}
\end{aligned}
$$

where

$$
\begin{aligned}
\int d^3x\bar{u}_\alpha(x)\gamma^3\lambda_iu_0(x)e^{i(\vec{q}-\vec{k})\cdot\vec{x}} &= \frac{F_{III\alpha}(|\vec{q}-\vec{k}|)}{|\vec{q}-\vec{k}|}[\epsilon_{3mn}k_m\sigma_n\lambda_i]_{\alpha,0}\\
&\quad+\frac{F_{IV\alpha}(|\vec{q}-\vec{k}|)}{|\vec{q}-\vec{k}|}[\sqrt{Q^2}-k_3+i\epsilon_{3mn}\sigma_mk_n\lambda_i]_{\alpha,0},
\end{aligned}
\qquad \text{(B.7)}
$$

with

$$\begin{aligned} F_{III\alpha}(k) &= -2i\frac{\partial}{\partial k}\int_0^\infty dr r g_0(r) f_\alpha(r)\int_\Omega d\Omega \mathcal{C}_\alpha Y_{l_\alpha 0}(\theta,\phi)e^{ikx\cos\theta}, \qquad \text{(B.8)}\\ F_{IV\alpha}(k) &= \frac{\partial}{\partial k}\int_0^\infty dr r[g_\alpha(r)f_0(r) - g_0(r)f_\alpha(r)]\int_\Omega d\Omega \mathcal{C}_\alpha Y_{l_\alpha 0}(\theta,\phi)e^{ikx\cos\theta}. \qquad \text{(B.9)} \end{aligned}$$

Finally, we get

$G_A^B(Q^2)|^{\alpha}_{SE;I}$

$$\begin{aligned} &= \frac{1}{2(2\pi F)^2}\int_0^\infty dk k^3 \frac{\omega_\Phi(k^2)F_{I\alpha}(k) - F_{II\alpha}(k)}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]}\\ &\times \int_{-1}^1 dx\Big\{\frac{ik(1-x^2)F_{III\alpha}(k_-)}{\sqrt{k_-^2}} + \frac{F_{IV\alpha}(k_-)}{\sqrt{k_-^2}}[\sqrt{Q^2}x + k(1-2x^2)]\Big\}\\ &\times {}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\frac{i}{2}f_{3ij}\lambda_j\lambda_i\sigma_3\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B \qquad \text{(B.10)} \end{aligned}$$

For $\alpha = 0$

$$\begin{aligned} F_{III}(k) &= -2\mathrm{i}\pi\int_0^\infty dr\int_0^\pi d\theta r^2 g(r)f(r)\sin 2\theta e^{ikr\cos\theta}, \qquad \text{(B.11)}\\ F_{IV}(k) &= 0. \qquad \text{(B.12)} \end{aligned}$$

Hence

$$\begin{aligned} G_A^B(Q^2)|_{SE;I} &= \frac{1}{(2\pi F)^2}\int_0^\infty dk\int_{-1}^1 dx k^4(1-x^2)F_{II}(k^2)F_{III}(k_-^2)\\ &\quad\times\frac{1}{\sqrt{k_-^2}}\Big[\frac{c_1^B}{\omega_\pi^2(k^2)} + \frac{c_2^B}{\omega_K^2(k^2)}\Big], \qquad \text{(B.13)} \end{aligned}$$

where

$$\begin{aligned} c_1^B &= \sum_{i,j=1}^{3} {}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\frac{i}{2}f_{3ij}\lambda_j\lambda_i\sigma_3\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B\\ &= \langle B\uparrow|\sum_{k=1}^{3}[\sigma_3\lambda_3]^{(k)}|B\uparrow\rangle, \qquad \text{(B.14)}\\ c_2^B &= \sum_{i,j=4}^{7}\langle B\uparrow|\sum_{k=1}^{3}[\frac{i}{2}f_{3ij}\lambda_j\lambda_i\sigma_3]^{(k)}|B\uparrow\rangle. \qquad \text{(B.15)} \end{aligned}$$

B.4 Self-Energy Diagram II (SE;II)

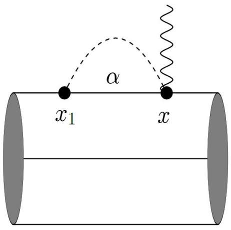

Figure B.4: Self-energy diagram II

$$
\begin{aligned}
&G_A^B(Q^2)\big|_{SE;II}^{\alpha}\\
&= 2\,{}^B\langle\phi_0|i\int\delta(t)d^4xd^4x_1e^{-\mathrm{i}qx}\\
&\quad\times N\Big\{\Big[-\frac{f_{3ij}}{2F}\bar{\psi}\gamma^3\lambda_i\psi\Phi_j\Big]_x\Big[\frac{1}{2F}\partial_\mu\Phi_m\bar{\psi}\gamma^\mu\gamma^5\lambda_m\psi\Big]_{x_1}\Big\}|\phi_0\rangle^B\\
&= \frac{2if_{3ij}}{4F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3xd^3x_1d^4ke^{i\vec{q}\cdot\vec{x}}\frac{e^{i\vec{k}\cdot(\vec{x}_1-\vec{x})}}{M_\Phi^2-k^2-i\epsilon}\\
&\quad\times\bar{u}_0(x)\gamma^\mu k_\mu\gamma^5\lambda_ju_\alpha(x)\bar{u}_\alpha(x_1)\gamma^3\lambda_iu_0(x_1)\\
&\quad\times\int dtdt_1\delta t\Theta(t-t_1)e^{-iq_0t}e^{-i\varepsilon_0(t_1-t)}e^{-i\varepsilon_\alpha(t-t_1)}e^{-ik_0(t-t_1)}b_0|\phi_0\rangle^B\\
&= \frac{f_{3ij}}{2F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3xd^3x_1d^3ke^{i\vec{q}\cdot\vec{x}}e^{i\vec{k}\cdot(\vec{x}-\vec{x}_1)}\\
&\quad\times\int dk_0\frac{1}{[\omega_\Phi(k^2)-k_0^2-i\epsilon][\Delta\varepsilon_\alpha+k_0-i\eta]}\\
&\quad\times\bar{u}_0(x)(\gamma^0k_0-\vec{\gamma}\cdot\vec{k})\gamma^5\lambda_ju_\alpha(x)\bar{u}_\alpha(x_1)\gamma^3\lambda_iu_0(x_1)b_0|\phi_0\rangle^B\\
&= \frac{i}{4F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\int d^3k\frac{f_{3ij}}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]}\\
&\quad\times\Big\{\frac{F_{III\alpha}(|\vec{q}+\vec{k}|)}{|\vec{q}+\vec{k}|}[\epsilon_{3mn}k_m\sigma_n\lambda_i]_{0,\alpha}\\
&\quad-\frac{F_{IV\alpha}(|\vec{q}+\vec{k}|)}{|\vec{q}+\vec{k}|}[\sqrt{Q^2}+k_3+i\epsilon_{3mn}\sigma_mk_n\lambda_i]_{0,\alpha}\Big\}\\
&\quad\times\big[\omega_\Phi(k^2)F_{I\alpha}^\dagger(k)-F_{II\alpha}^\dagger(k)\big][(\vec{\sigma}\cdot\vec{k})\lambda_j]_{\alpha,0}\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B, \qquad\qquad (B.16)
\end{aligned}
$$

It is similar to $G_A^B(Q^2)\big|_{SE;I}^{\alpha}$, we can obtain

$$
\begin{aligned}
& G_A^B(Q^2)\big|_{SE;II}^{\alpha} \\
& \quad = \frac{1}{2(2\pi F)^2}\int_0^\infty dk k^3 \frac{\omega_\Phi(k^2)F_{I\alpha}^\dagger(k) - F_{II\alpha}^\dagger(k)}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]} \\
& \qquad \times \int_{-1}^{1} dx \Big\{ \frac{ik(1-x^2)F_{V\alpha}(k_+)}{\sqrt{k_+^2}} + \frac{F_{IV\alpha}(k_+)}{\sqrt{k_+^2}}[\sqrt{Q^2}x+k)] \Big\} \\
& \qquad \times {}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger \frac{i}{2} f_{3ij}\lambda_j\lambda_i\sigma_3\chi_s\chi_f\chi_c b_0|\phi_0\rangle^B, \qquad \text{(B.17)}
\end{aligned}
$$

where

$$F_{V\alpha}(k) = -2i\frac{\partial}{\partial k}\int_0^\infty dr r g_\alpha(r) f_0(r) \int_\Omega d\Omega \mathcal{C}_\alpha Y_{l_\alpha 0}(\theta,\phi) e^{ikx\cos\theta}. \qquad \text{(B.18)}$$

When we restrict the quark propagator to the ground state,

$$G_A^B(Q^2)\big|_{SE;I} = G_A^B(Q^2)\big|_{SE;II}. \qquad \text{(B.19)}$$

B.5 Exchange Diagram (EX)

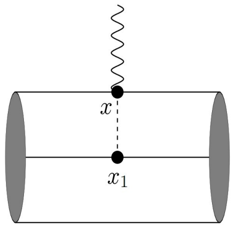

Figure B.5: Exchange diagram

$$
\begin{aligned}
G_A^B(Q^2)\big|_{EX} & \\
&= 2\,{}^B\langle\phi_0|i\int\delta(t)d^4xd^4x_1e^{-\mathrm{i}qx} \\
&\quad\times N\Big\{\Big[\frac{1}{2F}\partial_\mu\overbracket{\Phi_m\bar{\psi}\gamma^\mu\gamma^5\lambda_m\psi\Big]_{x_1}\Big[-\frac{f_{3ij}}{2F}\bar{\psi}\gamma^3\lambda_i\psi\Phi_j}\Big]_x\Big\}|\phi_0\rangle^B \\
&= \frac{if_{3ij}}{2F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger(x_1)b_0^\dagger(x)\int d^3xd^3x_1d^4ke^{i\vec{q}\cdot\vec{x}}\frac{e^{i\vec{k}\cdot(\vec{x}_1-\vec{x})}}{M_\Phi^2-k^2-i\epsilon} \\
&\quad\times\bar{u}_0(x_1)\gamma^\mu k_\mu\gamma^5\lambda_ju_0(x_1)\bar{u}_0(x)\gamma^3\lambda_iu_0(x) \\
&\quad\times\int dtdt_1\delta te^{-iq_0t}e^{-ik_0(t_1-t)}b_0(x)b_0(x_1)|\phi_0\rangle^B \qquad \text{(B.20)}
\end{aligned}
$$

Here, there is no quark propagator contribution to $G_A^B(Q^2)\big|_{EX}$, i.e., the ground state gives contribution only. Eq. (B.20) is similar to Eq. (B.6) when $\alpha = 0$.

$$
\begin{aligned}
G_A^B(Q^2)\big|_{EX} &= \frac{1}{4(2\pi F)^2}\int_0^\infty dk\int_{-1}^1 dxk^4(1-x^2)F_{II}(k^2))F_{III}(k_-^2) \\
&\quad\times\frac{1}{\sqrt{k_-^2}}\Big[\frac{c_3^B}{\omega_\pi^2(k^2)}+\frac{c_4^B}{\omega_K^2(k^2)}\Big]. \qquad \text{(B.21)}
\end{aligned}
$$

where

$$
c_3^B = \sum_{i,j,m,n=1}^{3}\langle B\uparrow|\sum_{\substack{k,l=1\\k\neq l}}^{3}f_{3ij}\epsilon_{3mn}[\sigma_m\lambda_j]^{(k)}[\sigma_n\lambda_i]^{(l)}|B\uparrow\rangle, \qquad \text{(B.22)}
$$

$$
c_4^B = \sum_{i,j,m,n=4}^{7}\langle B\uparrow|\sum_{\substack{k,l=1\\k\neq l}}^{3}f_{3ij}\epsilon_{3mn}[\sigma_m\lambda_j]^{(k)}[\sigma_n\lambda_i]^{(l)}|B\uparrow\rangle. \qquad \text{(B.23)}
$$

B.6 Vertex Correction Diagram (VC)

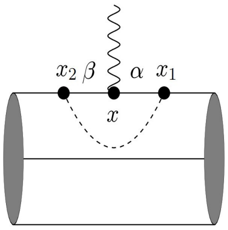

Figure B.6: Vertex correction diagram

$$
\begin{aligned}
&G_A^B(Q^2)\big|_{VC}^{\alpha\beta} \\
&= 4\,{}^B\langle\phi_0|\frac{-1}{2}\int \delta(t)d^4xd^4x_1d^4x_2e^{-\mathrm{i}qx} \\
&\quad\times N\Big\{\Big[\frac{1}{2F}\partial_\mu\Phi_i\bar{\psi}\gamma^\mu\gamma^5\lambda_i\psi\Big]_{x_1}\Big[\bar{\psi}\gamma^3\gamma^5\frac{\lambda_3}{2}\psi\Big]_x\Big[\frac{1}{2F}\partial_\nu\Phi_j\bar{\psi}\gamma^\nu\gamma^5\lambda_j\psi\Big]_{x_2}\Big\}|\phi_0\rangle^B \\
&= \frac{i}{8F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger\int d^3xd^3x_1d^3x_2d^4ke^{i\vec{q}\cdot\vec{x}}\frac{e^{i\vec{k}\cdot(\vec{x}_1-\vec{x}_2)}}{M_\Phi^2-k^2-i\epsilon} \\
&\quad\times\bar{u}_0(x_1)\gamma^\mu k_\mu\gamma^5\lambda_iu_\alpha(x_1)\bar{u}_\alpha(x)\gamma^3\gamma^5\lambda_3u_\beta(x)\bar{u}_\beta(x_2)\gamma^\nu k_\nu\gamma^5\lambda_iu_0(x_2) \\
&\quad\times\int dtdt_1dt_2\delta t\Theta(t_1-t)\Theta(t-t_2e^{-iq_0t}e^{-i\varepsilon_0(t_2-t_1)}e^{-i\varepsilon_\alpha(t_1-t)} \\
&\quad\times e^{-i\varepsilon_\beta(t-t_2)}e^{-ik_0(t_1-t_2)}b_0|\phi_0\rangle^B \\
&= \frac{-i}{8F^2(2\pi)^4}\,{}^B\langle\phi_0|b_0^\dagger d^3xd^3x_1d^3x_2d^3ke^{i\vec{q}\cdot\vec{x}}e^{i\vec{k}\cdot(\vec{x}_1-\vec{x}_2)} \\
&\quad\times\int dk_0\frac{1}{[\omega_\Phi(k^2)-(k_0)^2-i\epsilon][k_0+\Delta\varepsilon_\alpha-i\eta][k_0+\Delta\varepsilon_\beta-i\eta]} \\
&\quad\times\bar{u}_0(x_1)(\gamma^0k_0-\vec{\gamma}\cdot\vec{k})\gamma^5\lambda_iu_\alpha(x_1)\bar{u}_\alpha(x)\gamma^3\gamma^5\lambda_3u_\beta(x) \\
&\quad\times\bar{u}_\beta(x_2)(\gamma^0k_0-\vec{\gamma}\cdot\vec{k})\gamma^5\lambda_iu_0(x_2)b_0|\phi_0\rangle^B \\
&= -\frac{3G_A^N(Q^2)\big|_{LO}^\alpha}{40F^2(2\pi)^3}\,{}^B\langle\phi_0|b_0^\dagger\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger\int d^3k\frac{1}{\omega_\Phi(k^2)[\omega_\Phi(k^2)+\Delta\varepsilon_\alpha]^2} \\
&\quad\times\big[\omega_\Phi^2(k^2)F_{I\alpha}(k)F_{I\alpha}^\dagger(k)-\omega_\Phi(k^2)F_{I\alpha}(k)F_{II\alpha}^\dagger(k)-\omega_\Phi(k^2)F_{II\alpha}(k)F_{I\alpha}^\dagger(k) \\
&\quad+F_{II\alpha}(k)F_{II\alpha}^\dagger(k)\big]\lambda_i\lambda_3\lambda_i\int_\Omega d\Omega(\vec{\sigma}\cdot\vec{k})\sigma_3(\vec{\sigma}\cdot\vec{k})\chi_s\chi_f\chi_cb_0|\phi_0\rangle^B, \qquad \text{(B.24)}
\end{aligned}
$$

where

$$
\int d^3x\bar{u}_\alpha(x)\gamma^3\gamma^5\lambda_3u_\beta(x)e^{i\vec{q}\cdot\vec{x}} = \frac{3}{5}\delta_{\alpha\beta}G_A^N(Q^2)\big|_{LO}^\alpha\chi_c^\dagger\chi_f^\dagger\chi_s^\dagger[\sigma_3\lambda_3]_{\alpha\beta}\chi_s\chi_f\chi_c. \qquad \text{(B.25)}
$$

Finally, we have

$$G_A^B(Q^2)|_{VC}^{\alpha}$$

$$\begin{aligned}
= \; & \frac{1}{20(2\pi F)^2} G_A^N(Q^2)|_{LO}^{\alpha} \int dk k^4 \big[\omega_\Phi^2(k^2) F_{I\alpha}(k) F_{I\alpha}^\dagger(k) \\
& -\omega_\Phi(k^2) F_{I\alpha}(k) F_{II\alpha}^\dagger(k) - \omega_\Phi(k^2) F_{II\alpha}(k) F_{I\alpha}^\dagger(k) + F_{II\alpha}(k) F_{II\alpha}^\dagger(k)\big] \\
& \times \frac{{}^B\langle \phi_0 | b_0^\dagger \chi_c^\dagger \chi_f^\dagger \chi_s^\dagger \lambda_i \lambda_3 \lambda_i \sigma_3 \chi_s \chi_f \chi_c b_0 | \phi_0 \rangle^B}{\omega_\Phi(k^2)[\omega_\Phi(k^2) + \Delta\varepsilon_\alpha]^2}. \qquad \text{(B.26)}
\end{aligned}$$

For the ground state $\alpha = 0$, we obtain

$$\begin{aligned}
G_A^B(Q^2)|_{VC} &= \frac{1}{20(2\pi F)} G_A^N(Q^2)|_{LO} \int_0^\infty dk k^4 F_{II}^2(k^2) \\
& \times \left[\frac{c_1^B}{\omega_\pi^3(k^2)} + \frac{c_5^B}{\omega_\eta^3(k^2)} \right], \qquad \text{(B.27)}
\end{aligned}$$

where

$$\begin{aligned}
c_1^B &= {}^B\langle \phi_0 | b_0^\dagger \chi_c^\dagger \chi_f^\dagger \chi_s^\dagger \lambda_i \lambda_3 \lambda_i \sigma_3 \chi_s \chi_f \chi_c b_0 | \phi_0 \rangle^B \\
&= \sum_{i=1}^{3} \langle B \uparrow | \sum_{k=1}^{3} [\lambda_i \lambda_3 \lambda_i \sigma_3]^{(k)} | B \uparrow \rangle \\
&= \langle B \uparrow | \sum_{k=1}^{3} [\lambda_3 \sigma_3]^{(k)} | B \uparrow \rangle \qquad \text{(B.28)} \\
c_5^B &= \langle B \uparrow | \sum_{k=1}^{3} [\lambda_8 \lambda_3 \lambda_8 \sigma_3]^{(k)} | B \uparrow \rangle. \qquad \text{(B.29)}
\end{aligned}$$

Appendix C

Curriculum Vitae

C.1 Dr. Khanchai Khosonthongkee

School of Physics, Suranaree University of Technology

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EDUCATION

Ph.D. (Physics), 2004

Suranaree University of Technology, Thailand

Bachelor of Science (Physics), 1999

Mahidol University, Thailand

SELECTED PUBLICATIONS

1. X.Y. Liu, K. Khosonthongkee, A. Limphirat, P. Suebka, and Y. Yan, "Meson cloud contributions to baryon axial form factors", Phys. Rev. D 91, 034022 (2015).

2. A. Limphirat, W. Sreethawong, K. Khosonthongkee, and Y. Yan, "Reaction $e^+e^- \to \bar{D}D$ and ψ' mesons", Physical Review D 89, 054030 (2014).

3. X. Y. Liu, K. Khosonthongkee, A. Limphirat and Y. Yan, “Study of baryon octet electromagnetic form factors in perturbative chiral quark model”, J. Phys. G: Nucl. Part. Phys. 41, 055008 (2014).
4. Khanchai Khosonthongkee and Yupeng Yan, “Low-Lying Baryons in Hybrid Quark Model”, Few-Body Systems 55, 1037 (2014).
5. X. Y. Liu, K. Khosonthongkee, A. Limphirat and Y. Yan, “Study of baryon octet charge form factors in perturbative chiral quark model”, International Journal of Modern Physics: Conference Series 29, 1460252 (2014).
6. Amand Faessler, K. Khosonthongkee, C. Kobdaj, A. Limphirat, P. Suebka and Y. Yan, “Low-lying baryon decays in 3P0 quark model”, accepted for publication in J. Phys. G: Nucl. Part. Phys. 37, 115002 (2010).
7. Y. Yan, W. Poonsawat, K. Khosonthongkee, C. Kobdaj, P. Suebka, “Kaonic hydrogen atoms with realistic potentials”, Phys. Rev. C 81, 065208 (2010).
8. Y. Yan, K. Khosonthongkee, C. Kobdaj, P. Suebka, “ $e^+e^- \to N\bar{N}$ at Threshold and Proton Form Factor”, J. Phys. G: Nucl. Part. Phys. 37, 075007 (2010).
9. Y. Yan, C. Nualchimplee, P. Suebka, C. Kobdaj and K. Khosonthongkee, “Accurate evaluation of wave functions of pionium and kaonium”, Modern Physics Letters A 24, 901 (2009).
10. K. Kittimanapun, K. Khosonthongkee, C. Kobdaj, P. Suebka and Y. Yan, “ $e^+e^- \to \omega\pi$ reaction and $\rho(1450)$ and $\rho(1700)$ mesons in a quark model”, Phys. Rev. C79 025201 (2009).
11. Y. Yan, K. Khosonthongkee, C. Kobdaj, P. Suebka, Th. Gutsche, Amand Faessler and V.E. Lyubovitskij, “$\bar{p}D$ atoms in realistic potentials”, Physics Letter B 659, 555 (2008).
12. Y. Yan, P. Suebka, C. Kobdaj and K. Khosonthogkee, “Strong interaction in pionium”, Nuclear Physics A 790, 402c (2007).

13. K. Khosonthogkee, N. Supanam, Y. Yan, Th. Gutsche and Amand Faessler, "N*(1440) decays in a hybrid baryon model", Nuclear Physics A 790, 518c (2007).

14. K. Khosonthongkee, V.E. Lyubovitskij, Th. Gutsche, Amand Faessler, K. Pumsa-ard, S. Cheedket and Y. Yan, "Axial form factor of the nucleon in the perturbative chiral quark model", J. Phys. G: Nucl. Part. Phys. 30, 793 (2004).

C.2 Prof. Dr. Yupeng Yan

School of Physics, Suranaree University of Technology

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PROFESSIONAL EXPERIENCE

Professor (February 2007 - present)

School of Physics, Suranaree University of Technology, Thailand

Associate Professor (September 2002 - February 2007)

School of Physics, Suranaree University of Technology, Thailand

Assistant Professor (June 1999 - September 2002)

School of Physics, Suranaree University of Technology, Thailand

Lecturer (June 1997 - June 1999)

School of Physics, Suranaree University of Technology, Thailand

Research Officer (January 1996 - June 1997)

Department of Physics, University of the Witwatersrand, South Africa

FRD Post Doctoral Fellow (Foundation for Research Development of South Africa) (January 1995 - December 1995) Department of Physics, University of the Witwatersrand, South Africa

Lecturer (September 1987 - April 1990)

Department of Physics, Nankai University, P. R. China

DAAD Senior Visiting Researcher (Deutscher Akademischer Austauschdients) (November 2001 - Dcember 2001);

DAAD Senior Visiting Researcher (October 2000 - November 2000);

DAAD Visiting Researcher (April 1998 to June 1998,)

Institute for Theoretical Physics, Tuebingen University, Germany.

FRD Senior Research Officer (December 1999)

Department of Physics, University of the Witwatersrand, South Africa

Research Associate (July 1994 - December 1994),

Research Assistant (April 1990 - June 1994)

Institute for Theoretical Physics, Tuebingen University, Germany.

EDUCATION

Ph.D. in Physics (awarded on August 2, 1994)

Institute for Theoretical Physics, Tuebingen University, Germany.

Field of Study: Nuclear and Particle Theory

Title of Thesis: Nucleon-Antinucleon Bound States in Nonrelativistic Quark Models

Supervisor: Amand Faessler

Master of Science (awarded July 1987)

Department of Physics, Nankai University, P. R. China

Field of Study: Nuclear and Particle Theory

Title of Thesis: Vacuum Contribution to Nucleon-Nucleon Interaction

Supervisor: Guozu He

Bachelor of Science (awarded in July 1984)

Department of Physics, Nankai University, P. R. China

Field of Study: Electro-Optics

Title of Thesis: Design of Color-TV Bending Coil.

Supervisor: Shouqian Ding

AWARDS and RESEARCH GRANTS

SUT-National Research University project (2011-present) Research Center for Theoretical Physics

ThEP Fund (2009-present) Project: Study of strong interactions through exotic atoms, chiral perturbation theory and heavy ion collisions

CHE Fund (2007-2009) Project: Theoretical Physics

NRCT Fund (2006) Project: Dynamical Studies of Intermediate and High Energy Heavy Ion

SUT Fund (Oct. 2005 - Sep. 2007) Project: Study of Protonium Atoms in Sturmian Function Approach

NRCT Fund (NRCT: National Reaearch Council of Thailand) (Oct. 2001 - Sep. 2003) Project: Heavy Ion Reactions at Ultra-Relativistic Energies

RGJ Grant (RGJ: Royal Golden-Jubilee Ph.D. Project of Thailand, for more information see http://rgj.trf.or.th/eng.htm) (Oct. 2001 - Sep. 2006) Project: Low-Energy Pion-Proton Processes in Chiral Quark Models

RGJ Grant (October 2001 - September 2006) Project: Two-Pion and Two-Kaon Bound States in Chiral Quark Models

RGJ Grant (October 1998 - September 2003) Project: Baryon Weak and Electromagnetic Decays in Chiral Quark Models

RGJ Grant (October 1998 - September 2003) Project: Nucleon-Nucleon and Nucleon-Antinucleon Interactions

TRF Research Fund (Thailand Research Foundation) (Oct. 1997 - Sept. 1999) Suranaree University of Technology, Thailand

FRD Post Doctoral Fellowship (January 1995 - December 1995) (Foundation for Research Development of South Africa) University of the Witwatersrand, South Africa

Graduate Fellowship of Baden-Wuerttemberg of Germany (January 1992 - August 1994) Tuebingen University, Germany

INVITED LECTURES and TALKS:

The 9th conference on frontier topics of the interdisciplinary sciences of particle physics, nuclear physics and cosmology (July 20 - 24, 2010)

Talk: Decay widths of $X(1835)$ as $N\overline{N}$ bound state

Autumn School on Medium Energy Nuclear and Hadron Physics (October 8 - November 5, 2009)

Lectures: Antinucleon-nucleon interactions

International Workshop on the Physics of Excited Nucleon: NSTAR 2009 (April 19-22, 2009)

Talk: Electron-positron annihilation to nucleon-antinucleon pairs at low energies

The Fourth Asia-Pacific Conference on Few Body Problems in Physics (August 19-23, 2008)

Talk: Accurate evaluation of wave functions of pionium, kaonium and kaonic atom

The Third Asia-Pacific Conference on Few Body Problems in Physics (July 26-30, 2005)

Talk: Accurate Evaluation of Antiproton-Deuteron Atoms

CCAST World Laboratory Workshop (April 2-6, 2001)

China Center of the Advanced Science and Technology (CCAST), Beijing, P. R. China

Lectures: Proton-antiproton annihilation into two and three mesons (10 hours)

Nucleon-antinucleon atomic states (4 hours)

Quantum object is merely particle (4 hours)

(CCAST directed by T.D. Lee invites every year one outstanding young Chinese scholar working in each field abroad to give a series of lectures in Beijing)

Germany-East Asia Symposium of Nuclear and Particle Physics (May, 1998)

Talk: Proton-antiproton annihilation to two pions and two kaons

SELECTED PUBLICATIONS

1. X.Y. Liu, K. Khosonthongkee, A. Limphirat, P. Suebka, and Y. Yan, "Meson cloud contributions to baryon axial form factors", Phys. Rev. D 91, 034022 (2015).

2. W. Sreethawong, K. Xu and Y. Yan, “Exclusion of $c\bar{c}$ interpretation for X(3940)”, J. Phys. G: Nucl. Part. Phys. 42 025001 (2015).
3. C. Herold, M. Nahrgang, Y. Yan, C. Kobdaj, “Multiplicity fluctuations at the quark-hadron phase transition from a fluid dynamical model”, Journal of Physics: Conference Series 599, 12012 (2015).
4. S. J. Zheng, F. R. Xu, S. F. Shen, H. L. Liu, R. Wyss, and Y. P. Yan, “Shape coexistence and triaxiality in nuclei near ^{80}Zr”, Phys. Rev. C 90, 064309 (2014).
5. Christoph Herold, Marlene Nahrgang, Yupeng Yan and Chinorat Kobdaj, “Net-baryon number variance and kurtosis within nonequilibrium chiral fluid dynamics”, J. Phys. G: Nucl. Part. Phys. 41, 115106 (2014).
6. M. F. M. Lutz, D. Samart and Yupeng Yan, “Combined large-N_c and heavy-quark operator analysis for the chiral Lagrangian with charmed baryons”, Physical Review D 90, 056006 (2014).
7. Yu-Liang Yan, Dai-Mei Zhou, Ayut Limphirat, Bao-Guo Dong, Yu-Peng Yan and Ben-hao Sa, “Simultaneously study for particle transverse sphericity and ellipticity in pp collisions at LHC energies”, Nuclear Physics A 930, 187 (2014).
8. A. Limphirat, W. Sreethawong, K. Khosonthongkee, and Y. Yan, “Reaction $e^+e^- \to \bar{D}D$ and ψ' mesons”, Physical Review D 89, 054030 (2014).
9. Dai-Mei Zhou, Zeng-Zeng Luo, Yun Cheng, Ayut Limphirat, Yu-Liang Yan, Yu-Peng Yan, Xu Cai and Ben-hao Sa, “Comparative study for non-statistical fluctuation of net- Proton, baryon, and charge multiplicities”, J. Phys. G: Nucl. Part. Phys. 41, 065103 (2014).
10. X. Y. Liu, K. Khosonthongkee, A. Limphirat and Y. Yan, “Study of baryon octet electromagnetic form factors in perturbative chiral quark model”, J. Phys. G: Nucl. Part. Phys. 41, 055008 (2014).
11. Khanchai Khosonthongkee and Yupeng Yan, “Low-Lying Baryons in Hybrid Quark Model”, Few-Body Systems 55, 1037 (2014).

12. Wanchaloem Poonsawat, Ayut Limphirat, Dai-Mei Zhou, Yu-Liang Yan, Pornrad Srisawad, Chinorat Kobdaj, Yu-Peng Yan and Ben-hao Sa, "Net-Proton Nonstatistical Moments in High-Energy pp Collisions in PACIAE Model", Few-Body Systems 55, 1041 (2014).

13. X. Y. Liu, K. Khosonthongkee, A. Limphirat and Y. Yan, "Study of baryon octet charge form factors in perturbative chiral quark model", International Journal of Modern Physics: Conference Series 29, 1460252 (2014).

14. K. Xu, N. Ritjoho, S. Srisuphaphon and Y. Yan, "Estimation of ground state pentaquark masses", International Journal of Modern Physics: Conference Series 29, 1460251 (2014).

15. P. Srisawad, A. Harfield, S. Sombun, T. Katukum, O. Ketsungnoen, Y. M. Zheng, A. Limphirat and Y. Yan, "Influence of the in-medium kaon potential on kaon production in heavy ion collisions", Journal of Physics: Conference Series, 509, 012034 (2014).

16. Shuifa Shen, Guangbing Han, Shuxian Wen, Xuzhong Kang, Yupeng Yan, Zhijun Bai,Yican Wu, Xiaoguang Wu, Lihua Zhu, Guangsheng Li and Chuangye He, "High-Spin States and Level Structure in Stable Nucleus Strontium-84", Scientific Reports 3, 2740 (2013).

17. Shuifa Shen, Guangbing Han, Shuxian Wen, Yupeng Yan, Xiaoguang Wu, Lihua Zhu, Chuangye He, Guangsheng Li, "Magnetic rotation in Rubidium-84", Nuclear Science and Techniques 24, 030503 (2013).

18. P. Srisawad, Y. M. Zheng, A. Suksri, A. Harfield, A. Limphirat, Y. Yan, "In-Medium Kaon Potential and Nuclear Equation of State Measured in NucleusNucleus Collisions", Few-Body Systems, 54, 1449 (2013).

19. P. Srisawad, A. Suksri, S. Pholwiang, A. Harfield, Y. M. Zheng, Y. Yan, A. Limphirat, "Transverse mass spectra and rapidity distributions of K^+ in NI-NI collisions at 1.93 A GeV", Modern Physics Letters A, 28, 1350070 (2013).

20. Thomas Lang, Hendrik van Hees, Jan Steinheimer, Yu-Peng Yan and Marcus Bleicher, "Heavy quark transport at RHIC and LHC", J. Phys.: Conf. Ser. 426, 012032 (2013).

21. Christoph Herold, Yu-Peng Yan and Marcus Bleicher, “Signals for the QCD phase transition and critical point in a Langevin dynamical model”, J. Phys.: Conf. Ser. 426, 012008 (2013).

22. Chuangye He et al., “Signature splitting inversion and backbending in ^{80}Rb”, Phys. Rev. C 87, 034320 (2013).

23. W. Erni et al., “Technical design report for the PANDA (AntiProton Annihilations at Darmstadt) Straw Tube Tracker”, Eur. Phys. J. A 49, 25 (2013).

24. P. Srisawad, Y. M. Zheng, O. Katsungnoen, A. Limphirat and Y. Yan, “Azimuthal Distributions of K^+ Mesons in Heavy-Ion Collisions”, Few-Body Systems, 54, 303 (2013).

25. Ayut Limphirat, Dai-Mei Zhou, Yu-Liang Yan, Bao-Guo Dong, Chinorat Kobdaj, Yu-Peng Yan, Laszlo P. Csernai and Ben-Hao Sa, “PACIAE model capability in describing net proton moments”, Central European Journal of Physics, 10, 1388 (2012).

26. Dai-Mei Zhou, Ayut Limphirat, Yu-Liang Yan, Cheng Yun, Yu-Peng Yan, Xu Cai, Laszlo P. Csernai and Ben-Hao Sa, “Higher-moment singularities explored by net-proton nonstatistical fluctuations”, Phys. Rev. C 85, 064916 (2012).

27. D. Samart, Y. Yan, Th. Gutsche and Amand Faessler, “Decay width of X(1835) as Nucleon-Antinucleon Bound State”, Phys. Rev. D 85, 114033 (2012).

28. Zhao Yue, Kang Xu-Zhong, Shen Shui-Fa, Yan Yu-Peng, He Chuang-Ye, Yan Shi-Wei, “High-spin states in Transuranium Nuclei ^{242,244}Pu”, Chin. Phys. Lett. 29 (5), 052101 (2012).

29. Y. Yan and S. Srisuphaphon, “Construction of multiquark states in group theory”, Progress in Particle and Nuclear Physics 67, 496 (2012).

30. S. Srisuphaphon, Y. Yan, Th. Gutsche and V.E. Lyubovitskij, “ϕ meson production in $\bar{p}p$ annihilation at rest”, Phys. Rev. D 84, 074035 (2011).

31. Xuzhong Kang, Shuifa Shen et al., “Study of the Multiphonon γ-Vibrational Bands in Even-Even $^{176-190}$Pt Isotopes”, Journal of the Physical Society of Japan 80, 044201 (2011).
32. Dai-Mei Zhou, Ayut Limphirat, Yu-Liang Yan, Xiao-Mei Li, Yu-Peng Yan, Ben-Hao Sa, “Impact of parton rescattering on analysis of p+p collision data at LHC energies”, Phys. Lett. B 694, 435 (2011).
33. Nopmanee Supanam, Harold W. Fearing, Yupeng Yan, “Baryon chiral perturbation theory with virtual photons and leptons”, JHEP 11, 124 (2010).
34. Ayut Limphirat, Chinorat Kobdaj, Prasart Suebka and Yupeng Yan, “Decay width of ground and excited Ξ_b baryons in non-relativistic quark model” Phys. Rev. C 82, 055201 (2010).
35. Amand Faessler, K. Khosonthongkee, C. Kobdaj, A. Limphirat, P. Suebka and Y. Yan, “Low-lying baryon decays in 3P0 quark model”, accepted for publication in J. Phys. G: Nucl. Part. Phys. 37, 115002 (2010).
36. P. Srisawad, Y. M. Zheng, C. Fuchs, Amand Faessler, Y. Yan, C. Kobdaj and Y. Z. Xing, “Sigma meson production in proton-nucleus collisions”, International Journal of Modern Physics E 19, 1843 (2010).
37. Shuifa Shen et al., “High spin states and level structure in ^{84}Rb”, Phys. Rev. C 82, 014306 (2010).
38. Y. Yan, W. Poonsawat, K. Khosonthongkee, C. Kobdaj, P. Suebka, “Kaonic hydrogen atoms with realistic potentials”, Phys. Rev. C 81, 065208 (2010).
39. Y. Yan, K. Khosonthongkee, C. Kobdaj, P. Suebka, “ $e^+e^- \to N\bar{N}$ at Threshold and Proton Form Factor”, J. Phys. G: Nucl. Part. Phys. 37, 075007 (2010).
40. Y. Z. Xing, Y. M. Zheng, P. Srisawad and Y. Yan, “Influence of the Lorentz force on the centrality dependence of the kaon flow in heavy-ion collisions”, Europhysics Letters, 90, 12002 (2010).
41. Y. Z. Xing, Y. M. Zheng, P. Srisawad and Y. Yan, “Transverse momentum dependence of differential directed flow of Λ hyperon within kaon covariant

dynamics", Sci. China Phys. Mech. Astron. (Sci. China Ser. G) 53, 331 (2010).

42. P. Srisawad, Y. M. Zheng, Y. Yan and Y. Z. Xing, "Collective flow of K^+ meson within covariant Kaon dynamics", Nuclear Physics A 834, 590c (2010).

43. C. Nualchimplee, P. Suebka, Y. Yan and Amand Faessler, "Accurate evaluation of the 1s wave functions of kaonic hydrogen", Hyperfine Interact 193, 97 (2009).

44. Ayut Limphirat, Chinorat Kobdaj, Marcus Bleicher, Yupeng Yan and Horst Stoecker, "Strange and non-strange particle production in antiproton-nucleus collisions in the UrQMD model", J. Phys. G: Nucl. Part. Phys. 36, 064049 (2009).

45. Y. Yan, C. Nualchimplee, P. Suebka, C. Kobdaj and K. Khosonthongkee, "Accurate evaluation of wave functions of pionium and kaonium", Modern Physics Letters A 24, 901 (2009).

46. Pornrad Srisawad, Yu-Ming Zheng, Yupeng Yan, Chinorat Kobdaj and Yong-Zhong Xing, "Collective flow in heavy-ion collisions for E_b = 0.25 - 1.15 GeV/nucleon", Modern Physics Letters A 24, 1063 (2009).

47. K. Kittimanapun, K. Khosonthongkee, C. Kobdaj, P. Suebka and Y. Yan, " $e^+e^- \to \omega\pi$ reaction and $\rho(1450)$ and $\rho(1700)$ mesons in a quark model", Phys. Rev. C79 025201 (2009).

48. Y. Z. Xing, Y. M. Zheng, P. Srisawad, Y. Yan and C. Kobdaj, "Differential Directed Flow of K^+ Meson within Covariant Kaon Dynamics", Chinese Phys. Lett. 26, 022501 (2009).

49. Y. M. Zheng, C. Fuchs, P. Srisawad, A. Faessler, Y. Yan, C. Kobdaj and Y. Z. Xing, "Sigma meson production in nuclear reactions", Commun. Theor. Phys. 50, 725 (2008).

50. Y. Yan, K. Khosonthongkee, C. Kobdaj, P. Suebka, Th. Gutsche, Amand Faessler and V.E. Lyubovitskij, "$\bar{p}D$ atoms in realistic potentials", Physics Letter B 659, 555 (2008).

51. P. Srisawad, Y. M. Zheng, C. Fuchs, A. Faessler, Y. Yan, C. Kobdaj and Y.Z. Xing, "Sigma meson production in heavy ion collisions at intermediate energies", International Journal of Modern Physics A 22, 6219 (2007).
52. Y. Yan, P. Suebka, C. Kobdaj and K. Khosonthogkee, "Strong interaction in pionium", Nuclear Physics A 790, 402c (2007).
53. K. Khosonthogkee, N. Supanam, Y. Yan, Th. Gutsche and Amand Faessler, "N*(1440) decays in a hybrid baryon model", Nuclear Physics A 790, 518c (2007).
54. K. Pumsa-ard, W. Uchai and Y. Yan, "Meson exchange theory for high energy proton-proton scattering", International Journal of Modern Physics E, Vol. 15, No. 1 pp. 109-119 (2006).
55. P. Suebka, C. Kobdaj and Y. Yan, "$\pi\pi$ Reaction in non-relativistic quark model", International Journal of Modern Physics E, Vol. 14, No. 7 pp. 987-994 (2005).
56. Y. Yan, C. Kobdaj, P. Suebka, Y.M. Zheng, Amand Faessler, Th. Gutsche and V.E. Lyubovitskij, "Electron-positron annihilation into hadron-antihadron pairs", Phys. Rev. C71 025204 (2005).
57. P. Suebka and Y. Yan, "Accurate evaluation of pionium wave functions", Phys. Rev. C 70, 034006 (2004).
58. Yu-Ming Zheng, C. Fuchs, Amand Faessler, K. Shekhter, Yu-Peng Yan and Chinorat Kobdaj, "Covariant kaon dynamics and kaon flow in heavy ion collisions" Phys. Rev. C 69, 034907 (2004).
59. Ben-Hao Sa, Zhong-Qi Wang, Xu Cai, Dai-Mei Zhou, C. Kobdaj and Yu-Peng Yan, "Energy dependence of string fragmentation function and ϕ meson production" Commun. Theor. Phys. 41, 291 (2004).
60. Y. M. Zheng, C. Fuchs, Amand Faessler, K. Shekhter, P. Srisawad, Y. Yan and C. Kobdaj, "Influence of Chiral Mean Field on Kaon In-plane Flow in Heavy Ion Collisions" Commun. Theor. Phys. 41, 746 (2004).

61. K. Khosonthongkee, V.E. Lyubovitskij, Th. Gutsche, Amand Faessler, K. Pumsa-ard, S. Cheedket and Y. Yan, “Axial form factor of the nucleon in the perturbative chiral quark model”, J. Phys. G: Nucl. Part. Phys. 30, 793 (2004).
62. S. Cheedket, V.E. Lyubovitskij, Th. Gutsche, Amand Faessler, K. Pumsa-ard and Y. Yan, “Electromagnetic form factors of the baryon octet in the purterbative chiral quark model”, Eur. Phys. J. A. 20, 317 (2004).
63. Y. Yan, K. Pumsa-ard, R. Tegen, Th. Gutsche, V.E. Lyubovitskij and Amand Faessler, “Nucleon-Nucleon High-Energy Scattering”, Int. J. Mod. Phys. E 12, 367 (2003).
64. Y. Yan, C. Kobdaj, W. Uchai, A. Faessler, T. Gutsche and Y.M. Zheng, “Electron-Position Annihilation into Nucleon-Antinucleon Pairs”, Mod. Phys. Lett. A18, 370 (2003).
65. Y.M. Zheng, Z.L. Chu, C. Fuchs, A. Faessler, W. Xiao, D.P. Hua, Y. Yan, “Thansverse Flow of Kaons in Heavy-Ion Collisions”, Chin. Phys. Lett. 19, 926 (2002).
66. Y. Yan, “Baryon Structure and Baryon Interaction”, CCAST (World Laboratory) Workshop Series: Volume 129 (2001).
67. Y. Yan and R. Tegen, “On the Quark Substructure of the Hydrogen Nucleus”, Suranaree Journal of Science and Technology Vol. 7, 42 (2000).
68. Y. Yan and R. Tegen, “Proton-Antiproton to two Pions and two Kaons in Baryon Exchange and Meson Pole Diagrams”, Nucl. Phys. A648, 89 (1999).
69. Y. Yan and R. Tegen, “Scale Invariance of g_A/g_V in Dirac-scalar and Dirac-vector Quark Confining Potentials”, ISMPE 13 (1998).
70. Y. Yan, T. Gutsche, R. Thierauf, A. Muhn and A. Faessler, “Quasinuclear Nucleon-Antinucleon Bound States in the Quark Annihilation Model”, J. Phys. G23, 605 (1997).
71. Y. Yan, R. Tegen, T. Gutsche and A. Faessler, “Nucleon-Antinucleon Bound States and Sturmian Function Method”, Phys. Rev. C56, 1596 (1997).

72. E. Bauer, T. Gutsche, A. Muhm, R. Thierauf, Y. Yan, A. Faessler and R.V. Mau, “The Rho Parameter of Low-Energy Proton-Antiproton Scattering in the 3P0 Quark Model”, Phys. Lett. B386, 50 (1996).
73. Y. Yan and R. Tegen, “Role of Tensor Meson Pole and Delta Exchange Diagrams in Proton-Antiproton to two Pions”, Phys. Rev. C54, 1441 (1996).
74. A. Muhn, T. Gutsche, R. Thierauf, Y. Yan and A. Faessler, “Proton-Antiproton Annihilation into Two Mesons in the Quark Annihilation Model Including Final State Interaction”, Nucl. Phys. A598, 285 (1996).
75. R. Thierauf, T. Gutsche, Y. Yan, A. Muhm and A. Faessler, “The Non-Relativistic Quark Model and Nucleon-Antinucleon Interaction”, Nucl. Phys. A588, 783 (1995).
76. Y. Yan, S.W. Huang and A. Faessler, “A Microscopic Quark Model of Pion Nucleon to Kaon Sigma Reactions for Heavy Ion Collisions”, Phys. Lett. B354, 24 (1995).

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SELECTED PUBLICATIONS

1. X.Y. Liu, K. Khosonthongkee, A. Limphirat, P. Suebka, and Y. Yan, "Meson cloud contributions to baryon axial form factors", Phys. Rev. D 91, 034022 (2015).
2. Yu-Liang Yan, Dai-Mei Zhou, Ayut Limphirat, Bao-Guo Dong, Yu-Peng Yan and Ben-hao Sa, "Simultaneously study for particle transverse sphericity and ellipticity in pp collisions at LHC energies", Nuclear Physics A 930, 187 (2014).
3. A. Limphirat, W. Sreethawong, K. Khosonthongkee, and Y. Yan, "Reaction $e^+e^- \to \bar{D}D$ and ψ' mesons", Physical Review D 89, 054030 (2014).
4. Dai-Mei Zhou, Zeng-Zeng Luo, Yun Cheng, Ayut Limphirat, Yu-Liang Yan, Yu-Peng Yan, Xu Cai and Ben-hao Sa, "Comparative study for non-statistical fluctuation of net- Proton, baryon, and charge multiplicities", J. Phys. G: Nucl. Part. Phys. 41, 065103 (2014).
5. X. Y. Liu, K. Khosonthongkee, A. Limphirat and Y. Yan, "Study of baryon octet electromagnetic form factors in perturbative chiral quark model", J. Phys. G: Nucl. Part. Phys. 41, 055008 (2014).

6. Wanchaloem Poonsawat, Ayut Limphirat, Dai-Mei Zhou, Yu-Liang Yan, Pornrad Srisawad, Chinorat Kobdaj, Yu-Peng Yan and Ben-hao Sa, "Net-Proton Nonstatistical Moments in High-Energy pp Collisions in PACIAE Model", Few-Body Systems 55, 1041 (2014).

7. X. Y. Liu, K. Khosonthongkee, A. Limphirat and Y. Yan, "Study of baryon octet charge form factors in perturbative chiral quark model", International Journal of Modern Physics: Conference Series 29, 1460252 (2014).

8. P. Srisawad, A. Harfield, S. Sombun, T. Katukum, O. Ketsungnoen, Y. M. Zheng, A. Limphirat and Y. Yan, "Influence of the in-medium kaon potential on kaon production in heavy ion collisions", Journal of Physics: Conference Series, 509, 012034 (2014).

9. P. Srisawad, Y. M. Zheng, A. Suksri, A. Harfield, A. Limphirat, Y. Yan, "In-Medium Kaon Potential and Nuclear Equation of State Measured in NucleusNucleus Collisions", Few-Body Systems, 54, 1449 (2013).

10. P. Srisawad, A. Suksri, S. Pholwiang, A. Harfield, Y. M. Zheng, Y. Yan, A. Limphirat, "Transverse mass spectra and rapidity distributions of K^+ in NI-NI collisions at 1.93 A GeV", Modern Physics Letters A, 28, 1350070 (2013).

11. P. Srisawad, Y. M. Zheng, O. Katsungnoen, A. Limphirat and Y. Yan, "Azimuthal Distributions of K^+ Mesons in Heavy-Ion Collisions", Few-Body Systems, 54, 303 (2013).

12. Ayut Limphirat, Dai-Mei Zhou, Yu-Liang Yan, Bao-Guo Dong, Chinorat Kobdaj, Yu-Peng Yan, Laszlo P. Csernai and Ben-Hao Sa, "PACIAE model capability in describing net proton moments", Central European Journal of Physics, 10, 1388 (2012).

13. Dai-Mei Zhou, Ayut Limphirat, Yu-Liang Yan, Cheng Yun, Yu-Peng Yan, Xu Cai, Laszlo P. Csernai and Ben-Hao Sa, "Higher-moment singularities explored by net-proton nonstatistical fluctuations", Phys. Rev. C 85, 064916 (2012).

14. Dai-Mei Zhou, Ayut Limphirat, Yu-Liang Yan, Xiao-Mei Li, Yu-Peng Yan,

Ben-Hao Sa, “Impact of parton rescattering on analysis of p+p collision data at LHC energies”, Phys. Lett. B 694, 435 (2011).

15. Ayut Limphirat, Chinorat Kobdaj, Prasart Suebka and Yupeng Yan, “Decay width of ground and excited Ξ_b baryons in non-relativistic quark model” Phys. Rev. C 82, 055201 (2010).
16. Amand Faessler, K. Khosonthongkee, C. Kobdaj, A. Limphirat, P. Suebka and Y. Yan, “Low-lying baryon decays in 3P0 quark model”, accepted for publication in J. Phys. G: Nucl. Part. Phys. 37, 115002 (2010).
17. Ayut Limphirat, Chinorat Kobdaj, Marcus Bleicher, Yupeng Yan and Horst Stoecker, “Strange and non-strange particle production in antiproton-nucleus collisions in the UrQMD model”, J. Phys. G: Nucl. Part. Phys. 36, 064049 (2009).

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SELECTED PUBLICATIONS

1. Jan Kuckei, Claudio Dib, Amand Faessler, Thomas Gutsche, Sergey Kovalenko, Valery E. Lyubovitskij, Kem Pumsa-ard, "Strong CP violation and the neutron electric dipole form-factor", Phys. Atom. Nucl. 70, 349-357 (2007).

2. Amand Faessler, Thomas Gutsche, Barry R. Holstein, , Diana Nicmorus, Kem Pumsa-ard, "Light baryon magnetic moments and N → Delta gamma transition in a Lorentz covariant chiral quark approach", Phys. Rev. D 74, 074010 (2006).

3. K. Pumsa-Ard, W. Uchai, Y. Yan, "Meson exchange theory for high energy proton-proton scattering", Int. J. Mod. Phys. E 15, 109-119 (2006).

4. Amand Faessler, Th. Gutsche, M.A. Ivanov, J.G. Korner, V.E. Lyubovitskij, D. Nicmorus, K. Pumsa-ard, "Magnetic moments of heavy baryons in the relativistic three-quark model", Phys. Rev. D 73, 094013 (2006).

5. Claudio Dib, Amand Faessler, Thomas Gutsche, Sergey Kovalenko, Jan Kuckei, Valery E. Lyubovitskij, Kem Pumsa-ard, "The Neutron electric dipole form-factor in the perturbative chiral quark model", J. Phys. G32, 547-564 (2006).
6. Amand Faessler, Th. Gutsche, V.E. Lyubovitskij, K. Pumsa-ard, "Chiral dynamics of baryons in a Lorentz covariant quark model", Phys. Rev. D 73, 114021 (2006).
7. Yu-bing Dong, Amand Faessler, Thomas Gutsche, Jan Kuckei, Valery E. Lyubovitskij, Kem Pumsa-ard, Peng-Nian Shen, "Nucleon polarizabilities in the perturbative chiral quark model", J. Phys. G32, 203-220 (2006).
8. K. Khosonthongkee, V.E. Lyubovitskij, Th. Gutsche, Amand Faessler, K. Pumsa-ard, S. Cheedket and Y. Yan, "Axial form factor of the nucleon in the perturbative chiral quark model", J. Phys. G: Nucl. Part. Phys. 30, 793 (2004).
9. S. Cheedket, V.E. Lyubovitskij, Th. Gutsche, Amand Faessler, K. Pumsa-ard and Y. Yan, "Electromagnetic form factors of the baryon octet in the purterbative chiral quark model", Eur. Phys. J. A. 20, 317 (2004).
10. Y. Yan, K. Pumsa-ard, R. Tegen, Th. Gutsche, V.E. Lyubovitskij and Amand Faessler, "Nucleon-Nucleon High-Energy Scattering", Int. J. Mod. Phys. E 12, 367 (2003).

Appendix D

Publication

1. X. Y. Liu, K. Khosonthongkee, A. Limphirat, P. Suebka and Y. Yan, "Meson cloud contributions to baryon axial form factors," Phys. Rev. D **91**, no. 3, 034022 (2015).

PHYSICAL REVIEW D **91,** 034022 (2015)

Meson cloud contributions to baryon axial form factors

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The axial form factor as well as the axial charges and radii of octet N, Σ, and Ξ baryons are studied in the perturbative chiral quark model with the quark wave functions predetermined by fitting the theoretical results of the proton charge form factor to experimental data. The theoretical results are found, based on the predetermined quark wave functions, in good agreement with experimental data and lattice values. This may indicate that the electric charge and axial charge distributions of the constituent quarks are the same. The study reveals that the meson cloud plays an important role in the axial charge of octet baryons, contributing 30%–40% to the total values, and strange sea quarks have a considerable contribution to the axial charges of the Σ and Ξ.

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I. INTRODUCTION

The form factors play an extremely important role in hadron physics since they supply necessary information on the internal structure and electroweak interaction properties. The Q^2 dependence of the electromagnetic and axial form factors of the nucleon have been studied in a cloudy bag model [1,2], lattice QCD [3–8], and other approaches [9–16], in which the theoretical results are comparable with experimental data. The experimental and theoretical understanding of the electromagnetic and axial nucleon structure at low energy have been reviewed in Refs. [17,18]. In recent years, the hyperon axial charges, which are the axial form factors in zero recoil, have been predicted in lattice QCD [19,20], the chiral perturbation theory [21], and the relativistic constituent quark model (RCQM) [22]. However, there are few theoretical works on the Q^2 dependence of the axial form factor of hyperons, especially in the chiral quark model. This inspires us to study the axial form factors of octet baryons in the perturbative chiral quark model (PCQM).

The PCQM [23–33] is a powerful tool to study the baryon structure and properties in the low-energy particle physics. However, the previous work on the axial form factor of the nucleon [30] shows that the PCQM theoretical result of the nucleon axial form factor is in good agreement with the experimental data only at very low momentum transfer Q^2, descending quickly with the momentum transfer Q^2 increasing. It is noted that a variational Gaussian ansatz has been employed for the quark wave functions [30]. As we argue in Ref. [23], the Gaussian-type quark wave functions of baryons lead to the theoretical predictions for the form factors of baryons consistent with experimental data only at very low momentum transfer Q^2. Furthermore, the more reasonable quark wave functions have been determined in Ref. [23] by fitting the PCQM theoretical result of the proton charge form factor to the experimental data, as shown in Fig. 1. In addition, the Q^2 dependence of the theoretical electromagnetic form factors with the determined wave functions in the region $Q^2 \leq 1\ \mathrm{GeV}^2$ is consistent with experimental data. More details

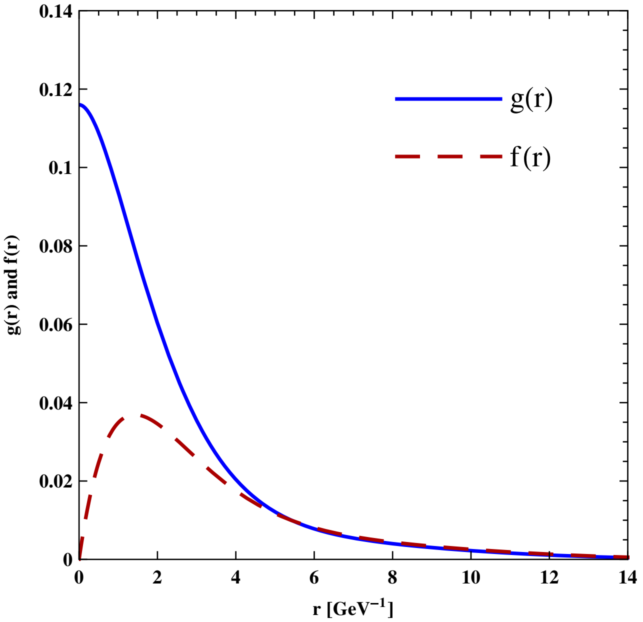

FIG. 1 (color online). Normalized radial wave functions of the valence quarks for the upper component $g(r)$ and the lower component $f(r)$ with the central values of the expansion coefficients, which are determined by fitting the theoretical results of the proton charge form factor to the experimental data [23].

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could be found in Ref. [23]. In this work, we attempt to study the axial form factors of octet baryons in the PCQM with the determined wave functions in SU(3) and analyze the strangeness contributions to the axial form factors. We also predict the axial charges of light hyperons (Σ and Ξ). There are no further parameters to be adjusted in the present work.

The paper is organized as follows. In Sec. II, we present the theoretical expressions of octet baryon axial form factors in the PCQM. The numerical results based on the predetermined quark wave functions and discussion are given in Sec. III.

II. AXIAL FORM FACTORS IN THE PCQM

In the framework of the PCQM, the axial form factors $G_A^B(Q^2)$ of octet baryons in the Breit frame are defined by

$$\begin{aligned}&\chi^\dagger_{B_{s'}}\frac{\vec{\sigma}_B}{2}\chi_{B_s}G_A^B(Q^2)\\&\quad={}^B\langle\phi_0|\sum_{n=0}^{2}\frac{\mathrm{i}^n}{n!}\int\delta(t)d^4x d^4x_1\cdots d^4x_n e^{-\mathrm{i}q\cdot x}\\&\qquad\times T[\mathcal{L}_I^W(x_1)\cdots\mathcal{L}_I^W(x_n)\vec{A}_3(x)]|\phi_0\rangle_c^B,\end{aligned}\tag{1}$$

where the state vector $|\phi_0\rangle^B$ corresponds to the unperturbed three-quark states projected onto the respective baryon states, which are constructed in the framework of the $SU(6)$ spin-flavor and $SU(3)$ color symmetry. The subscript c in Eq. (1) refers to contributions from connected graphs only. χ_{B_s} and $\chi^\dagger_{B_{s'}}$ are the baryon spin wave functions in the initial and final states, and $\vec{\sigma}_B$ is the baryon spin matrix. $G_A^B(Q^2)$ are the axial form factors of octet baryons with the squared momentum transfer Q^2.

The quark-meson interaction Lagrangian $\mathcal{L}_I^W(x)$ in Eq. (1) takes the form

$$\begin{aligned}\mathcal{L}_I^W(x)&=\frac{1}{2F}\partial_\mu\Phi_i(x)\bar{\psi}(x)\gamma^\mu\gamma^5\lambda^i\psi(x)\\&\quad+\frac{f_{ijk}}{4F^2}\Phi_i(x)\partial_\mu\Phi_j(x)\bar{\psi}(x)\gamma^\mu\lambda_k\psi(x),\end{aligned}\tag{2}$$

where $F=88$ MeV; ψ is the triplet of u, d, and s quark fields; and Φ_i are the octet meson fields. The axial-vector current A_i^μ in Eq. (1) is given by

$$\begin{aligned}A_i^\mu&=F\partial^\mu\Phi_i+\bar{\psi}\gamma^\mu\gamma^5\frac{\lambda_i}{2}\psi-\frac{f_{ijk}}{2F}\bar{\psi}\gamma^\mu\lambda_j\psi\Phi_k\\&\quad+\bar{\psi}(\hat{Z}-1)\gamma^\mu\gamma^5\frac{\lambda_i}{2}\psi+o(\Phi_i^2),\end{aligned}\tag{3}$$

where the renormalization constant $\hat{Z}$ is determined by the nucleon charge conservation condition as

$$\begin{aligned}\hat{Z}&=1-\frac{3}{4(2\pi F)^2}\int_0^\infty dkk^4F_I^2(k^2)\\&\quad\times\left[\frac{1}{\omega_\pi^3(k^2)}+\frac{2}{3\omega_K^3(k^2)}+\frac{1}{9\omega_\eta^3(k^2)}\right],\end{aligned}\tag{4}$$

with $\omega_\Phi(k^2)=\sqrt{M_\Phi^2+k^2}$ and the vertex function $F_I(k)$ for the $qq\Phi$ system taking the form

$$\begin{aligned}F_I(k)&=2\pi\int_0^\infty drr^2\int_0^\pi d\theta\sin\theta e^{ikr\cos\theta}\\&\quad\times[g(r)^2+f(r)^2\cos2\theta].\end{aligned}\tag{5}$$

The ground-state quark wave function $u_0(\vec{x})$ may, in general, be expressed as

$$u_0(\vec{x})=\begin{pmatrix}g(r)\\ i\vec{\sigma}\cdot\hat{x}f(r)\end{pmatrix}\chi_s\chi_f\chi_c,\tag{6}$$

where χ_s, χ_f, and χ_c are the spin, flavor, and color quark wave functions, respectively. In the numerical analysis, we employ the radial quark wave functions $g(r)$ and $f(r)$ that have been extracted in Ref. [23] by fitting the theoretical results of the proton charge form factor to the experimental data. More information on the PCQM and quark wave functions can be found in Ref. [23].

The Feynman diagrams contributing to the axial form factor of octet baryons in accordance with the $\mathcal{L}_I^W(x)$ in Eq. (2) and the A_i^μ in Eq. (3) are shown in Fig. 2. The corresponding analytical expressions for the relevant diagrams are derived as follows:

(a) Three-quark core leading-order (LO) diagram:

$$\begin{aligned}G_A^B(Q^2)|_{\mathrm{LO}}&=c_1^B2\pi\int_0^\infty drr^2\int_0^\pi d\theta\sin\theta e^{iQr\cos\theta}\\&\quad\times[g(r)^2+f(r)^2\cos(2\theta)].\end{aligned}\tag{7}$$

(b) Three-quark core counterterm (CT) diagram:

$$G_A^B(Q^2)|_{\mathrm{CT}}=(\hat{Z}-1)G_A^B(Q^2)|_{\mathrm{LO}}.\tag{8}$$

(c) Self-energy I (SE I) diagram:

$$\begin{aligned}G_A^B(Q^2)|_{\mathrm{SE:I}}&=\frac{1}{2(2\pi F)^2}\int_0^\infty dkk^4\int_{-1}^1dx(1-x^2)\\&\quad\times\frac{F_I(k)F_{II}(k_-)}{\sqrt{k_-^2}}\left[\frac{c_1^B}{\omega_\pi^2(k^2)}+\frac{c_2^B}{\omega_K^2(k^2)}\right],\end{aligned}\tag{9}$$

where $k_-=\sqrt{k^2+Q^2-2k\sqrt{Q^2}x}$, and the vertex function for the quark-pion-axial vector current $F_{II}(k)$ is given by

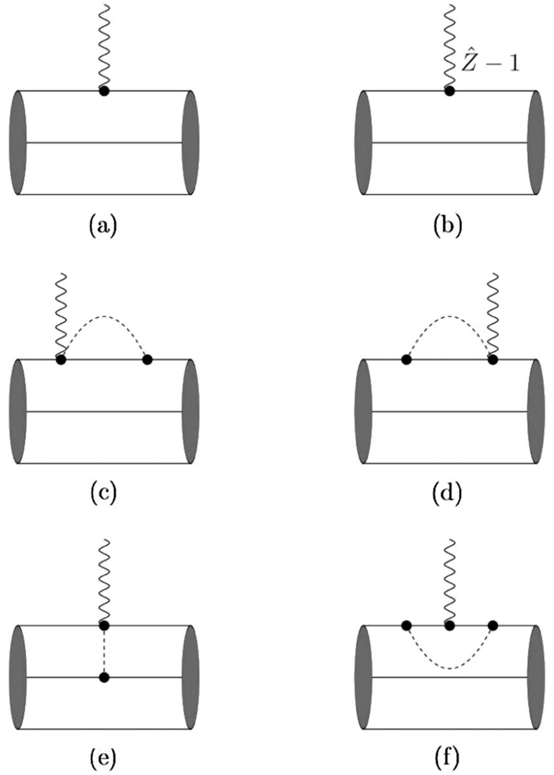

FIG. 2. Diagrams contributing to the axial form factor of octet baryons: 3q-core leading order (a), 3q-core counterterm (b), self-energy I (c), self-energy II (d), meson exchange (e), and vertex correction (f).

$$F_{II}(k) = -2i\pi \int_0^\infty drr^2 \times \int_0^\pi d\theta g(r) f(r) \sin 2\theta e^{ikr\cos\theta}. \qquad (10)$$

(d) Self-energy II (SE II) diagram:

$$G_A^B(Q^2)|_{\mathrm{SE:II}} = \frac{1}{2(2\pi F)^2} \int_0^\infty dkk^4 \int_{-1}^1 dx(1-x^2) \times \frac{F_I(k)F_{II}(k_-)}{\sqrt{k_-^2}} \left[\frac{c_1^B}{\omega_\pi^2(k^2)} + \frac{c_2^B}{\omega_K^2(k^2)}\right]. \qquad (11)$$

(e) Exchange (EX) diagram:

$$G_A^B(Q^2)|_{\mathrm{EX}} = \frac{1}{4(2\pi F)^2} \int_0^\infty dkk^4 \int_{-1}^1 dx(1-x^2) \times \frac{F_I(k)F_{II}(k_-)}{\sqrt{k_-^2}} \left[\frac{c_3^B}{\omega_\pi^2(k^2)} + \frac{c_4^B}{\omega_K^2(k^2)}\right]. \qquad (12)$$

TABLE I. The constants c_i^B for the octet baryons axial form factors $G_A^B(Q^2)$.

	c_1	c_2	c_3	c_4	c_5
N	5/3	5/6	8	0	−5/9
Σ	4/3	2/3	0	4	−4/9
Ξ	−1/3	−1/6	0	−4	1/9

(f) Vertex-correction (VC) diagram:

$$G_A^B(Q^2)|_{\mathrm{VC}} = \frac{1}{20(2\pi F)^2} \int_0^\infty dkk^4 F_I^2(k) \times \left[\frac{c_1^B}{\omega_\pi^3(k^2)} + \frac{c_5^B}{\omega_\eta^3(k^2)}\right] \cdot G_A^N(Q^2)|_{\mathrm{LO}}. \qquad (13)$$

The constants c_i^B are given in Table I. It is noted that the constant $c_1^N = 5/3$ in Eq. (7) is determined by the spin and flavor of the three-quark core of the nucleon, namely, the naive SU(3) quark model. In addition, Eqs. (9) and (11) present the same results for the diagrams (c) and (d) of Fig. 2 based on the T symmetry.

III. NUMERICAL RESULTS AND DISCUSSION

In this section, we present the axial charges and form factors of octet baryons with the determined quark wave functions [23]. The calculations are extended to the SU(3) flavor symmetry, including π, kaon, and η-meson cloud contributions. Note that there are no further parameters in the following numerical calculations on the axial form factors of octet baryons.

The numerical results for the axial charges, which are the diagonal axial charges shown in Eq. (1) with $\vec{A}_3$, are listed in Table II. The uncertainties in the total values of the axial charges caused by the fitting errors of the quark wave functions [23] (the same hereinafter in Table III) are estimated around 15%. As shown in Table II, the theoretical results reveal that the meson cloud plays an important role in the axial charge of octet baryons, contributing 30%–40% to the total values. Except for the N, there are no direct experimental data for the axial charge of the Σ and Ξ, and thus we have the chiral extrapolation estimations of lattice QCD results at the physical m_π point [19] compiled in the table for comparison. It is found that the theoretical N axial charge is in good agreement with the experimental value [34], and the work predictions on Σ and Ξ axial charges are consistent with the lattice QCD values [19]. In Ref. [22], the axial charges of hyperons are evaluated in the RCQM without considering the chiral symmetry. Our tree-level (LO) results of the Σ and Ξ axial charges are comparable with the RCQM values while the meson loop diagrams contribute some correction to our tree-level results of g_A^B.

TABLE II. Numerical results for the octet baryon axial charges g_A^B, where the uncertainties are from the errors of the quark wave functions. The experimental data are taken from Ref. [34], while the chiral extrapolation estimations of lattice QCD results at the physical m_π point are taken from Ref. [19].

	3q	Meson loops			
	LO	CT + SE + EX + VC	Total	Lattice [19]	Data [34]
g_A^N	0.883	0.418	1.301 ± 0.230	1.180 ± 0.100	1.272 ± 0.002
g_A^Σ	0.707	0.220	0.927 ± 0.132	0.900 ± 0.096	...
g_A^Ξ	−0.177	−0.106	-0.283 ± 0.033	-0.277 ± 0.034	...

Listed in Table III are the axial radii of octet baryons, which are derived by

$$\langle r_A^2 \rangle_B = -6 \frac{1}{g_A^B} \frac{dG_A^B(Q^2)}{dQ^2}\bigg|_{Q^2=0}. \tag{14}$$

The nucleon axial radius $\langle r_A^2 \rangle_N^{1/2}$ in Table III is a little bit larger than the experimental value, and the predicted results for the $\langle r_A^2 \rangle_\Sigma^{1/2}$ and $\langle r_A^2 \rangle_\Xi^{1/2}$ are in the same order as $\langle r_A^2 \rangle_N^{1/2}$ since our calculations are restricted to the SU(3) chiral symmetry. As discussed in Ref. [30], the contributions of excited-state quarks in loop diagrams generate some corrections to the N axial form factor. The inclusion of the excited-state quarks in loop diagrams may be addressed in a future work.

TABLE III. Numerical results for the octet baryon axial radii $\langle r_A^2 \rangle_B^{1/2}$ (in units of fm), where the uncertainties are from the errors of the quark wave functions. The experimental data are taken from Ref. [17].

	PCQM	Data [17]
$\langle r_A^2 \rangle_N^{1/2}$	0.808 ± 0.088	0.639 ± 0.010
$\langle r_A^2 \rangle_\Sigma^{1/2}$	0.832 ± 0.089	...
$\langle r_A^2 \rangle_\Xi^{1/2}$	0.780 ± 0.087	...

TABLE IV. Contribution of π, K, and η mesons to the axial charges g_A^B.

		Meson loops	
	π	K	η
g_A^N	0.375	0.045	−0.002
g_A^Σ	0.118	0.104	−0.002
g_A^Ξ	−0.030	−0.077	−0.001

TABLE V. Strange sea quark contributions of the individual loop diagrams of Fig. 2 to the axial charges g_A^B.

	CT	SE	EX	VC
g_A^N	−0.0136	0.0567	0	−0.0006
g_A^Σ	−0.0109	0.0453	0.0680	−0.0004
g_A^Ξ	0.0027	−0.0113	−0.0680	0.0001

Furthermore, we have studied the separate contribution of π, K, and η mesons to the axial charges. As shown in Table IV, the π meson contribution to the N axial charge dominates over the ones from the K and η mesons, but the K meson contributions to the Σ and Ξ axial charges are in the same order as the π ones. It is noticed that the contribution from the η meson is negligible. We also list in Table V the strange sea quark contributions (K and η meson clouds) of the individual loop diagrams as shown in Fig. 2 to the axial charges g_A^B. Based on Eqs. (7)–(13), we may point out the fact that the K meson contributes to the SE and EX diagrams, while the η meson participates in the VC process only. The results listed in Table V reveal that the strange sea quark contribution to the N axial charge is caused mainly by the SE diagram, but to the Σ and Ξ axial

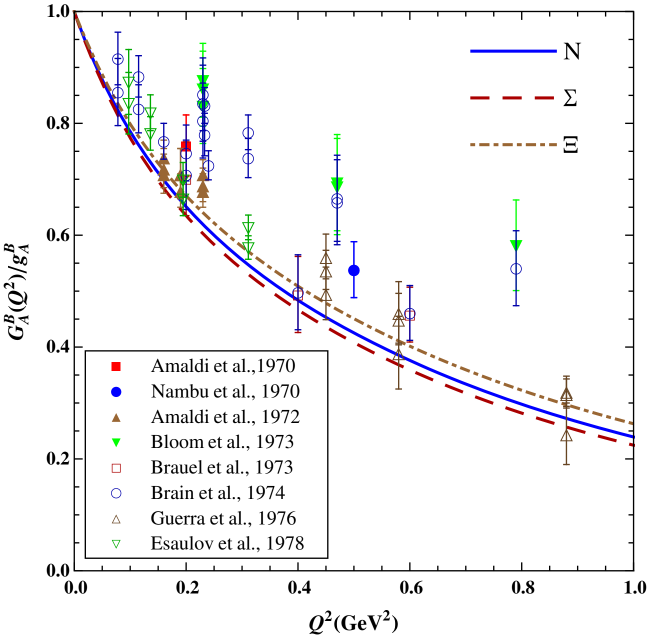

FIG. 3 (color online). Normalized axial form factors $G_A^B(Q^2)/g_A^B$ of octet baryons. The experimental data on nucleon axial form factor are taken from Refs. [35–42].

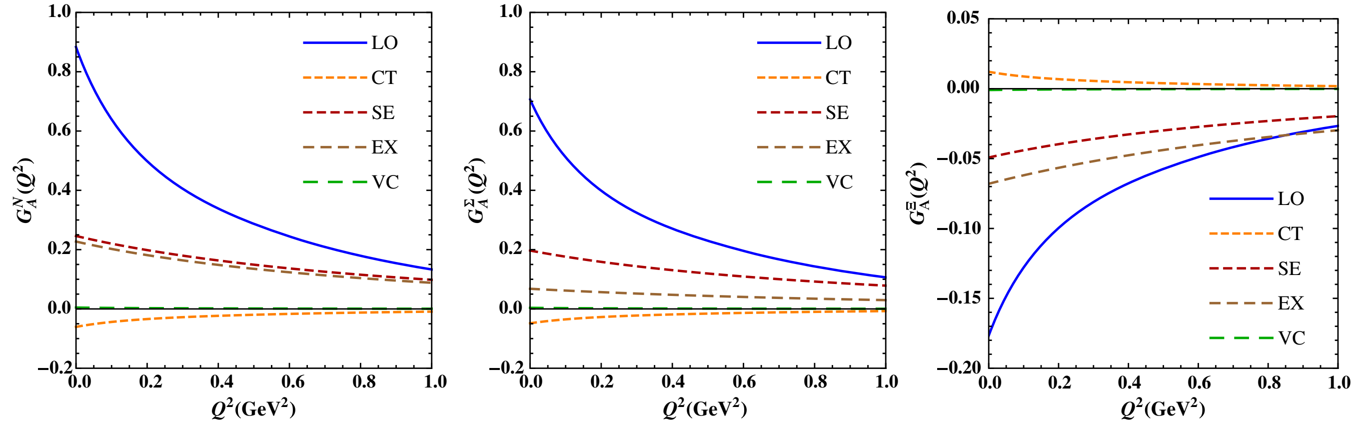

FIG. 4 (color online). The individual contributions of the different diagrams of Fig. 2 to the axial form factors of octet baryons (left panel for N, middle panel for Σ, and right panel for Ξ).

charges, both the SE and EX diagrams are important. As shown in the last column of Table V, the η meson contribution is suppressed due to the weak coupling between the s current quark and η meson.

We show the Q^2 dependence of the axial form factors of octet baryons in Fig. 3, which are normalized to 1 at zero recoil, with the experimental data on the nucleon axial form factor [35–42] plotted as well. As shown in Fig. 3, the result for $G_A^N(Q^2)$ is close to the experimental data [35–42], and the predicted results on $G_A^\Sigma(Q^2)$ and $G_A^\Xi(Q^2)$ show a similar Q^2 dependence based on the SU(3) symmetry. Considering the PQCM result of g_A^N is 2.5% larger than the experimental value, the non-normalized result for $G_A^N(Q^2)$ could be in better agreement with the experimental data. As expected, the theoretical axial form factors fall off smoothly when the momentum transfer Q^2 increases. The predetermined quark wave functions employed in the work take a form similar to Coulomb wave functions and have large values at small r region as shown in Fig. 1, compared to the Gaussian-type wave functions employed in the previous work [30]. This may be the main reason why the theoretical axial form factor evaluated with the predetermined wave functions is consistent with the experimental data especially at larger Q^2.

We present in Fig. 4 the contribution of various processes as shown in Fig. 2 to the axial form factors of octet baryons. It is found that the sea quark or meson cloud contributes to axial form factors mainly through the SE and EX diagrams. The LO diagram results in a dipolelike axial form factor, while the meson cloud leads to a flat contribution to the axial form factor. The flat contribution indicates that the sea quarks distribute mainly in a very small region, which is rather surprising and needs to be further studied.

In summary, one may conclude that the fact that the theoretical results of the axial form factors and axial charges agree well with experimental data and lattice QCD values, with the predetermined quark core wave functions in the electromagnetic sector, may indicate that the electric charge and axial charge distributions of the constituent quarks are the same. The study reveals that the meson cloud plays an important role in the axial charge of octet baryons, contributing 30%–40% to the total values, and strange sea quarks have a considerable contribution to the axial charge of the Σ and Ξ.

The center-of-mass correction has been considered in relativistic quark models in Refs. [43–45]. The nucleon mass is very sensitive to the center-of-mass effect, decreasing some 40% [45], while the theoretical results in Ref. [43] reveal that the center-of-mass correction reduces the magnetic moments of the nucleon by about 10%. Therefore, it is necessary to investigate the center-of-mass correction in the PCQM in our future work.

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[1] S. Théberge and A. W. Thomas, Nucl. Phys. **A393**, 252 (1983).
[2] A. W. Thomas, *Advances in Nuclear Physics* (Springer, New York, 1984), Vol. 13, pp. 1—37.
[3] K. F. Liu, S. J. Dong, T. Draper, J. M. Wu, and W. Wilcox, Phys. Rev. D **49**, 4755 (1994).
[4] H. W. Lin and K. Orginos, Phys. Rev. D **79**, 074507 (2009).

[5] T. Yamazaki, Y. Aoki, T. Blum, H. W. Lin, S. Ohta, S. Sasaki, R. Tweedie,, and J. Zanotti, Phys. Rev. D **79**, 114505 (2009).

[6] S. N. Syritsyn *et al.*, Phys. Rev. D **81**, 034507 (2010).

[7] C. Alexandrou, M. Brinet, J. Carbonell, M. Constantinou, P. A. Harraud, P. Guichon, K. Jansen, T. Korzec, and M. Papinutto, Phys. Rev. D **83**, 045010 (2011).

[8] T. Bhattacharya, S. D. Cohen, R. Gupta, A. Joseph, H. W. Lin, and B. Yoon, Phys. Rev. D **89**, 094502 (2014).

[9] I. C. Cloet, D. B. Leinweber, and A. W. Thomas, Phys. Rev. C **65**, 062201 (2002).

[10] H. H. Matevosyan, A. W. Thomas, and G. A. Miller, Phys. Rev. C **72**, 065204 (2005).

[11] M. R. Schindler and S. Scherer, Eur. Phys. J. A **32**, 429 (2007).

[12] G. Ramalho and M. T. Peña, J. Phys. G **36**, 115011 (2009).

[13] G. Erkol and A. Ozpineci, Phys. Rev. D **83**, 114022 (2011).

[14] G. Eichmann and C. S. Fischer, Eur. Phys. J. A **48**, 9 (2012).

[15] G. Ramalho and K. Tsushima, Phys. Rev. D **84**, 054014 (2011); **86**, 114030 (2012).

[16] G. Ramalho, K. Tsushima, and A. W. Thomas, J. Phys. G **40**, 015102 (2013).

[17] V. Bernard, L. Elouadrhiri, and U. G. Meißner, J. Phys. G **28**, R1 (2002).

[18] J. Arrington, C. D. Roberts, and J. M. Zanotti, J. Phys. G **34**, S23 (2007).

[19] H. W. Lin and K. Orginos, Phys. Rev. D **79**, 034507 (2009).

[20] G. Erkol, M. Oka, and T. T. Takahashi, Phys. Lett. B **686**, 36 (2010).

[21] F. J. Jiang and B. C. Tiburzi, Phys. Rev. D **78**, 017504 (2008); **80**, 077501 (2009).

[22] K. S. Choi, W. Plessas, and R. F. Wagenbrunn, Phys. Rev. D **82**, 014007 (2010).

[23] X. Y. Liu, K. Khosonthongkee, A. Limphirat, and Y. Yan, J. Phys. G **41**, 055008 (2014).

[24] V. E. Lyubovitskij, T. Gutsche, A. Faessler, and E. G. Drukarev, Phys. Rev. D **63**, 054026 (2001).

[25] V. E. Lyubovitskij, T. Gutsche, and A. Faessler, Phys. Rev. C **64**, 065203 (2001).

[26] V. E. Lyubovitskij, T. Gutsche, A. Faessler, and M. R. Vinh, Phys. Lett. B **520**, 204 (2001).

[27] V. E. Lyubovitskij, T. Gutsche, A. Faessler, and R. Vinh Mau, Phys. Rev. C **65**, 025202 (2002).

[28] K. Pumsa-ard, V. E. Lyubovitskij, T. Gutsche, A. Faessler, and S. Cheedket, Phys. Rev. C **68**, 015205 (2003).

[29] S. Cheedket, V. E. Lyubovitskij, T. Gutsche, A. Faessler, K. Pumsa-ard, and Y. Yan, Eur. Phys. J. A **20**, 317 (2004).

[30] K. Khosonthongkee, V. E. Lyubovitskij, T. Gutsche, A. Faessler, K. Pumsa-ard, S. Cheedket, and Y. Yan, J. Phys. G **30**, 793 (2004).

[31] Y. Dong, A. Faessler, T. Gutsche, J. Kuckei, V. E. Lyubovitskij, K. Pumsa-ard, and P. Shen, J. Phys. G **32**, 203 (2006).

[32] C. Dib, A. Faessler, T. Gutsche, S. Kovalenko, J. Kuckei, V. E. Lyubovitskij, and K. Pumsa-ard, J. Phys. G **32**, 547 (2006).

[33] A. Faessler, T. Gutsche, V. E. Lyubovitskij, and C. Oonariya, J. Phys. G **35**, 025005 (2008).

[34] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[35] E. Amaldi, B. Borgia, P. Pistilli, M. Balla, G. V. Di Giorgio, A. Giazotto, S. Serbassi, and G. Stoppini, Nuovo Cimento A **65**, 377 (1970).

[36] Y. Nambu and M. Yoshimura, Phys. Rev. Lett. **24**, 25 (1970).

[37] E. Amaldi, M. Benevantano, B. Borgia, F. De Notaristefani, A. Frondaroli, P. Pistilli, I. Sestili, and M. Severi, Phys. Lett. B **41**, 216 (1972).

[38] E. D. Bloom, R. L. A. Cottrell, H. DeStaebler, C. L. Jordan, H. G. Piel, C. Y. Prescott, R. Siemann, S. Stein, and R. E. Taylor, Phys. Rev. Lett. **30**, 1186 (1973).

[39] P. Brauel *et al.*, Phys. Lett. B **45**, 389 (1973).

[40] B. J. Read, Nucl. Phys. **B74**, 482 (1974).

[41] A. D. Guerra, A. Giazotto, M. A. Giorgi, A. Stefanini, D. R. Botterill, H. E. Montgomery, P. R. Norton, and G. Matone, Nucl. Phys. **B107**, 65 (1976).

[42] A. S. Esaulov, A. M. Pilipenko, and Y. I. Titov, Nucl. Phys. **B136**, 511 (1978).

[43] D. H. Lu, A. W. Thomas, and A. G. Williams, Phys. Rev. C **57**, 2628 (1998).

[44] Y. B. Dong, K. Shimizu, A. Faessler, and A. J. Buchmann, Phys. Rev. C **60**, 035203 (1999).

[45] E. M. Tursunov and S. Krewald, Phys. Rev. D **90**, 074015 (2014).