光前夸克模型中重子电磁衰变$\Xi_c'^+ \to \Xi_c^+\gamma$ 计算

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2022年06月20日

研究动机

- $M_{\Xi_c'^+} - M_{\Xi_c^+} = 2578.4 - 2467.94 = 110.46 MeV < 139.57(M_\pi)$，因此只能发生电磁衰变。
- 采用光前夸克模型(LF QM)计算非微扰物理量，概念简单，唯象可行且应用方便。
- 受郑海洋老师文章(arxiv:2109.01216)启发，我们采用LF QM计算其电磁衰变。

TABLE XXIII: Electromagnetic decay rates (in units of keV) of S-wave charmed baryons. Among the four different results listed in [260] and [266], we quote those denoted by $\Gamma_\gamma^{(0)}$ and "Present (ecqm)", respectively.

Decay	HHChPT [256, 259]	HBChPT [258]	Dey [260]	Ivanov [261]	Simonis [262]	Aliev [263]	Wang [264]	Bernotas [265]	Majethiya [266]	Hazra [267]
$\Sigma_c^+ \to \Lambda_c^+\gamma$	91.5	65.6 ± 2	120	60.7 ± 1.5	74.1	50 ± 17		46.1	60.55	93.5 ± 0.7
$\Sigma_c^{*+} \to \Lambda_c^+\gamma$	150.3	161.6 ± 5	310	151 ± 4	190	130 ± 45		126	154.48	231 ± 7
$\Sigma_c^{*++} \to \Sigma_c^{++}\gamma$	1.3	1.20 ± 0.6	1.6		1.96	2.65 ± 1.20	$6.36^{+6.79}_{-3.31}$	0.826	1.15	1.48 ± 0.02
$\Sigma_c^{*+} \to \Sigma_c^+\gamma$	0.002	0.04 ± 0.03	0.001	0.14 ± 0.004	0.011	0.40 ± 0.16	$0.40^{+0.43}_{-0.21}$	0.004	$< 10^{-4}$	$(7 \pm 1)10^{-4}$
$\Sigma_c^{*0} \to \Sigma_c^0\gamma$	1.2	0.49 ± 0.1	1.2		1.41	0.08 ± 0.03	$1.58^{+1.68}_{-0.82}$	1.08	1.12	1.38 ± 0.02
$\Xi_c'^+ \to \Xi_c^+\gamma$	19.7	5.43 ± 0.33	14	12.7 ± 1.5	17.3	8.5 ± 2.5		10.2		21.4 ± 0.3
$\Xi_c^{*+} \to \Xi_c^+\gamma$	63.5	21.6 ± 1	71	54 ± 3	72.7	52 ± 25		44.3	63.32	81.9 ± 0.5
$\Xi_c^{*+} \to \Xi_c'^+\gamma$	0.06	0.07 ± 0.03	0.10		0.063	0.274	$0.96^{+1.47}_{-0.67}$	0.011		0.03 ± 0.00
$\Xi_c'^0 \to \Xi_c^0\gamma$	0.4	0.46	0.33	0.17 ± 0.02	0.185	0.27 ± 0.6		0.0015		0.34 ± 0.01
$\Xi_c^{*0} \to \Xi_c^0\gamma$	1.1	1.84	1.7	0.68 ± 0.04	0.745	0.66 ± 0.32		0.908	0.30	1.32 ± 0.01
$\Xi_c^{*0} \to \Xi_c'^0\gamma$	1.0	0.42 ± 0.16	1.6		1.33	2.14	$1.26^{+0.80}_{-0.46}$	1.03		1.26 ± 0.03
$\Omega_c^{*0} \to \Omega_c^0\gamma$	0.9	0.32 ± 0.20	0.71		1.13	0.932	$1.16^{+1.12}_{-0.54}$	1.07	2.02	1.14 ± 0.13

LF QM 计算$\mathcal{B}(1/2) \to \mathcal{B}(1/2)$ 电磁衰变形状因子

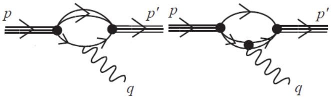


Figure: The electromagnetic couplings of the baryons. The left and right panels show the contribution from the quark and diquarks.

电磁形状因子定义：

$$\left\langle \mathcal{B}'\left(p', s'\right) \left| J_\mu(0) \right| \mathcal{B}(p, s) \right\rangle = \bar{u}\left(p', s'\right) \left[\gamma_\mu F_1\left(q^2\right) + \frac{i\sigma_{\mu\nu} q^\nu}{M + M'} F_2\left(q^2\right) \right] u(p, s). \quad (1)$$

其中$F_1\left(q^2\right)$，$F_2\left(q^2\right)$ 分别是Dirac形状因子和Pauli形状因子。电磁流$J^\mu = \bar{q}\,\Gamma^\mu\, q$，与虚光子耦合顶角$\Gamma^\mu$ [1,2]，

$$\Gamma^\mu_{Q\gamma Q} = e_Q \gamma^\mu \quad (2)$$

$$\Gamma^\mu_{S\gamma S} = -\frac{i}{3}(k_1 + k_1')^\mu \quad (3)$$

$$\Gamma^\mu_{A\gamma A} = ie_A \left\{ g_{\alpha\beta}(k_1 + k_1')^\mu - \left[(1+\kappa)k_{1\beta} - (\kappa + \xi)k'_{1\beta}\right] g^\mu_\alpha - \left[(1+\kappa)k'_{1\alpha} - (\kappa+\xi)k_{1\alpha}\right] g^\mu_\beta \right\} \quad (4)$$

[1]J. He and Y. b. Dong, J. Phys. G 32 (2006), 189-202.

[2]T. D. Lee and C. N. Yang, Phys. Rev. 128 (1962), 885-898.

电磁形状因子

Dirac和Pauli形状因子Eq. (1) 可以通过“+”抽取得到，

$$F_1\left(q^2\right)=\left\langle p',\uparrow\left|\frac{J^+}{2p^+}\right|p,\uparrow\right\rangle,\qquad -\mathbf{q}_\perp\frac{F_2\left(q^2\right)}{M+M'}=\left\langle p',\uparrow\left|\frac{J^+}{2p^+}\right|p,\downarrow\right\rangle.$$

- 如果一个光子从夸克Q辐射出，(Fig. 1左图), 形状因子$F_Q(q^2)$，

$$F_{1Q}\left(q^2\right)=\left\langle p',\uparrow\left|\frac{e_Q\gamma^+}{2p^+}\right|p,\uparrow\right\rangle, \tag{5}$$

$$-\mathbf{q}_\perp\frac{F_{2Q}\left(q^2\right)}{M+M'}=\left\langle p',\uparrow\left|\frac{e_Q\gamma^+}{2p^+}\right|p,\downarrow\right\rangle. \tag{6}$$

可以得到，

$$F_{1Q}\left(q^2\right)=e_Q\int\frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3}\frac{\phi'^*_{nL'}\left(x',k'_\perp\right)\phi_{1L}\left(x,k_\perp\right)}{8P^+P'^+\sqrt{x\bar{x}\left(k'_1\cdot\bar{P}'+m'_1M'_0\right)\left(k_1\cdot\bar{P}+m_1M_0\right)}}$$
$$\times\,\mathrm{Tr}\left[\left(\bar{\not{P}}+M_0\right)\gamma^+\left(\bar{\not{P}}'+M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}'_1+m'_1\right)\gamma^+\left(\not{k}_1+m_1\right)\Gamma_{LS_{[qq]}J_l}\right], \tag{7}$$

$$F_{2Q}\left(q^2\right)=e_Q\cdot\frac{-i(M+M')q^i_\perp}{\mathbf{q}^2_\perp}\int\frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3}\frac{\phi'^*_{nL'}\left(x',k'_\perp\right)\phi_{1L}\left(x,k_\perp\right)}{8P^+P'^+\sqrt{x\bar{x}\left(k'_1\cdot\bar{P}'+m'_1M'_0\right)\left(k_1\cdot\bar{P}+m_1M_0\right)}}$$
$$\times\,\mathrm{Tr}\left[\left(\bar{\not{P}}+M_0\right)\sigma^{i+}\left(\bar{\not{P}}'+M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}'_1+m'_1\right)\gamma^+\left(\not{k}_1+m_1\right)\Gamma_{LS_{[qq]}J_l}\right], \tag{8}$$

电磁形状因子

- 如果一个光子从di-夸克$S(A)$辐射出，(Fig. 1右图), 形状因子$F_{S(A)}(q^2)$,

$$F_{1S(A)}\left(q^2\right) = \left\langle p', \uparrow \left| \frac{\Gamma^+_{S(V)}}{2p^+} \right| p, \uparrow \right\rangle, \tag{9}$$

$$-\mathbf{q}_\perp \frac{F_{2S(A)}\left(q^2\right)}{M+M'} = \left\langle p', \uparrow \left| \frac{\Gamma^+_{S(V)}}{2p^+} \right| p, \downarrow \right\rangle. \tag{10}$$

then

$$F_{1S(A)}\left(q^2\right) = \int \frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3} \frac{\phi'^*_{nL'}\left(x', k'_\perp\right)\phi_{1L}\left(x, k_\perp\right)}{8P^+P'^+\sqrt{x\bar{x}\left(k'_1\cdot\bar{P}' + m'_1 M'_0\right)\left(k_1\cdot\bar{P} + m_1 M_0\right)}}$$
$$\times \operatorname{Tr}\left[\left(\bar{\not{P}} + M_0\right)\gamma^+\left(\bar{\not{P}}' + M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}_2 + m_2\right)\Gamma_{LS_{[qq]}J_l}\cdot\Gamma^+_{S(A)}\right], \tag{11}$$

$$F_{2S(A)}\left(q^2\right) = \cdot\frac{-i(M+M')q^i_\perp}{\mathbf{q}^2_\perp}\int \frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3} \frac{\phi'^*_{nL'}\left(x', k'_\perp\right)\phi_{1L}\left(x, k_\perp\right)}{8P^+P'^+\sqrt{x\bar{x}\left(k'_1\cdot\bar{P}' + m'_1 M'_0\right)\left(k_1\cdot\bar{P} + m_1 M_0\right)}}$$
$$\times \operatorname{Tr}\left[\left(\bar{\not{P}} + M_0\right)\sigma^{i+}\left(\bar{\not{P}}' + M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}_2 + m_2\right)\Gamma_{LS_{[qq]}J_l}\cdot\Gamma^+_{S(A)}\right], \tag{12}$$

最后，可以得到，

$$F_1(q^2) = F_{1Q}(q^2) + F_{1S(A)}(q^2), \tag{13}$$

$$F_2(q^2) = F_{2Q}(q^2) + F_{2S(A)}(q^2). \tag{14}$$

重子波函数

物理形状因子为标量di-夸克和轴矢di-夸克跃迁形状因子的线性组合，

$$[\text{ form factor }]^{\text{physical}}\left(q^2\right) = c_S \times [\text{ form factor }]_S + c_A \times [\text{ form factor }]_A$$

其中c_S 和c_A分别是重子的标量和轴矢量di-夸克重叠因子，从重子初态和末态的味道自旋波函数推导得到。
强子矩阵元可以改写为，

$$\begin{aligned}\left\langle\mathcal{B}'\left|j_\mu\right|\mathcal{B}\right\rangle = & c_S\left\langle Q\left[q_1 q_2\right]_S\left|j_\mu\right| Q\left[q_1 q_2\right]_S\right\rangle \\ & + c_A\left\langle Q\left[q_1 q_2\right]_A\left|j_\mu\right| Q\left[q_1 q_2\right]_A\right\rangle .\end{aligned}$$

味道自旋波函数

- (q_2, q_3) 为标量di-quark

$$|q_1\,(q_2q_3)_S\,,\uparrow\rangle \equiv q_1\uparrow(q_2q_3)_S\,,$$

这里$(q_2q_3)_S=(q_2q_3)_{00}=(q_2q_3)\left(\frac{1}{\sqrt{2}}(\uparrow\downarrow-\downarrow\uparrow)\right)$.

- (q_2, q_3) 为轴矢量di-quark

$$|q_1\,(q_2q_3)_A\,,\uparrow\rangle \equiv \sqrt{\frac{2}{3}}q_1\downarrow(q_2q_3)_{11}-\sqrt{\frac{1}{3}}q_1\uparrow(q_2q_3)_{10}\,,$$

这里$(q_2q_3)_{11}=(q_2q_3)(\uparrow\uparrow)$，$(q_2q_3)_{10}=(q_2q_3)\left(\frac{1}{\sqrt{2}}(\uparrow\downarrow+\downarrow\uparrow)\right)$.

可以证明，

$$q_1q_2q_3\left(\frac{1}{\sqrt{6}}(\uparrow\downarrow\uparrow+\downarrow\uparrow\uparrow-2\uparrow\uparrow\downarrow)\right)=-\frac{\sqrt{3}}{2}\,|q_1\,(q_2q_3)_S\,,\uparrow\rangle+\frac{1}{2}\,|q_1\,(q_2q_3)_A\,,\uparrow\rangle\,. \tag{15}$$

$$q_1q_2q_3\left(\frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow-\downarrow\uparrow\uparrow)\right)=-\frac{1}{2}\,|q_1\,(q_2q_3)_S\,,\uparrow\rangle-\frac{\sqrt{3}}{2}\,|q_1\,(q_2q_3)_A\,,\uparrow\rangle\,, \tag{16}$$

味道自旋波函数

- 味道对称六重态$\mathcal{B}^{6}_{cq_1q_2}(\Xi_c'^{+})$,

$$\left|\mathcal{B}^{6}_{cq_1q_2},\uparrow\right\rangle = \left(\frac{1}{\sqrt{2}}\left(q_1q_2 + q_2q_1\right)c\right)\left(\frac{1}{\sqrt{6}}(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)\right),$$

  其中$(q_1, q_2) = (u, s)$.
- 味道反对称三重态$\mathcal{B}^{\bar{3}}_{cq_1q_2}(\Xi_c^{+})$,

$$\left|\mathcal{B}^{\bar{3}}_{cq_1q_2},\uparrow\right\rangle = \left(\frac{1}{\sqrt{2}}\left(q_1q_2 - q_2q_1\right)c\right)\left(\frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)\right)$$

  其中$(q_1, q_2) = (u, s)$.

根据上述表达式，可以推导出di-夸克基中初态和末态的重子波函数:

$$\Xi_c'^{+} = \frac{1}{\sqrt{2}}\left(-c\,(us)_A - c\,(su)_A\right) \tag{17}$$

$$\Xi_c^{+} = \frac{1}{\sqrt{2}}\left(c\,(us)_S - c\,(su)_S\right) \tag{18}$$

重叠因子$C_{S(A)}$

$$\begin{aligned}\left\langle \Xi_c \left| j_\mu \right| \Xi_c'^{+} \right\rangle =& c_S \left\langle q_1 \left[q_2 q_3\right]_S \left| j_\mu \right| q_1 \left[q_2 q_3\right]_S \right\rangle \\ &+ c_A \left\langle q_1 \left[q_2 q_3\right]_A \left| j_\mu \right| q_1 \left[q_2 q_3\right]_A \right\rangle .\end{aligned}$$

- $q_1 = c, \quad c_S = 0\,, c_A = 0\,.$
- $q_1 = s, \quad c_S = -\frac{\sqrt{3}}{4}\,, c_A = \frac{\sqrt{3}}{4}\,.$
- $q_1 = u, \quad c_S = \frac{\sqrt{3}}{4}\,, c_A = -\frac{\sqrt{3}}{4}\,.$

$$\Xi_c'^{+} = \frac{\sqrt{3}}{2} s(cu)_S + \frac{1}{2} s(cu)_A = \frac{\sqrt{3}}{2} u(cs)_S + \frac{1}{2} u(cs)_A \tag{19}$$

$$\Xi_c^{+} = -\frac{1}{2} s(cu)_S + \frac{\sqrt{3}}{2} s(cu)_A = \frac{1}{2} u(cs)_S - \frac{\sqrt{3}}{2} u(cs)_A \tag{20}$$

Note:Eqs.(19,20)参看文章[3]

[3]X. H. Hu, R. H. Li and Z. P. Xing, Eur. Phys. J. C **80** (2020) no.4, 320.

di-夸克电荷$e_{S(A)}$

质子和中子波函数:

$$|\text{proton}^{\uparrow}\rangle = \frac{1}{\sqrt{18}}[(2d_{11}^{\uparrow}\mathcal{N}^{\downarrow} - \sqrt{2}d_{11}^{\rightarrow}\mathcal{N}^{\uparrow} - \sqrt{2}d_{10}^{\uparrow}\mathcal{P}^{\downarrow} + d_{10}^{\rightarrow}\mathcal{P}^{\uparrow})\sin\alpha + 3t_{00}\mathcal{P}^{\uparrow}\cos\alpha],$$

$$|\text{proton}^{\downarrow}\rangle = \frac{1}{\sqrt{18}}[(2d_{11}^{\downarrow}\mathcal{N}^{\uparrow} - \sqrt{2}d_{11}^{\rightarrow}\mathcal{N}^{\downarrow} - \sqrt{2}d_{1-1}^{\downarrow}\mathcal{P}^{\uparrow} + d_{10}^{\rightarrow}\mathcal{P}^{\downarrow})\sin\alpha + 3t_{00}\mathcal{P}^{\downarrow}\cos\alpha],$$

$$|\text{neutron}^{\uparrow}\rangle = \frac{1}{\sqrt{18}}[(-2d_{1-1}^{\uparrow}\mathcal{P}^{\downarrow} + \sqrt{2}d_{1-1}^{\rightarrow}\mathcal{P}^{\uparrow} + \sqrt{2}d_{10}^{\uparrow}\mathcal{N}^{\downarrow} - d_{10}^{\rightarrow}\mathcal{N}^{\uparrow})\sin\alpha + 3t_{00}\mathcal{N}^{\uparrow}\cos\alpha],$$

$$|\text{neutron}^{\downarrow}\rangle = \frac{1}{\sqrt{18}}[(-2d_{1-1}^{\downarrow}\mathcal{P}^{\uparrow} + \sqrt{2}d_{1-1}^{\rightarrow}\mathcal{P}^{\downarrow} + \sqrt{2}d_{10}^{\downarrow}\mathcal{N}^{\uparrow} - d_{10}^{\rightarrow}\mathcal{N}^{\downarrow})\sin\alpha + 3t_{00}\mathcal{N}^{\downarrow}\cos\alpha],$$

Note that the electric charges of diquark states are

$$\langle d_{11}|\text{charge}|d_{11}\rangle = \tfrac{4}{3},$$

自旋同位旋，同位旋第三分量

$$\langle d_{10}|\text{charge}|d_{10}\rangle = \tfrac{1}{3},$$

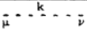
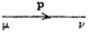
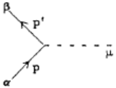
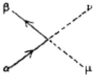
$$\langle d_{1-1}|\text{charge}|d_{1-1}\rangle = -\tfrac{2}{3},$$

and

$$\langle t_{00}|\text{charge}|t_{00}\rangle = \tfrac{1}{3}.$$

谢谢!

费曼规则：3矢量顶角[2]

Element	Graph	Value
Internal photon line		$D = -i\delta_{\mu\nu}(k^2)^{-1}$
Internal meson line		$S = -i(p^2+m^2-i\epsilon)^{-1}(\delta_{\mu\nu}+m^{-2}p_\mu p_\nu)$ $+ i(p^2+\xi^{-1}m^2-i\epsilon)^{-1}(m^{-2}p_\mu p_\nu)$
3-vertex		$V = ie\,[\delta_{\alpha\beta}(p+p')_\mu - \delta_{\alpha\mu}(-\kappa p'+p+\kappa p-\xi p')_\beta$ $- \delta_{\beta\mu}(-\kappa p+p'+\kappa p'-\xi p)_\alpha]$
4-vertex		$U = -ie^2[2\delta_{\mu\nu}\delta_{\alpha\beta}-(1-\xi)\delta_{\alpha\mu}\delta_{\beta\nu}$ $- (1$

4. NEGATIVE METRIC

In the ξ formalism, the propagator $\mathcal{S}$ in Fig. 2 consists of two parts: a spin-one part $-i(p^2+m^2-i\epsilon)^{-1} \times (\delta_{\mu\nu}+m^{-2}p_\mu p_\nu)$ and a spin-zero part $i(p^2+\xi^{-1}m^2+i\epsilon)^{-1} \times (m^{-2}p_\mu p_\nu)$. At first sight, it might appear that the presence of the spin-zero part acts like a regulator; therefore, we might have a renormalizable theory for

$$\varepsilon^*_{I\mu}(k,s_2)\cdot\varepsilon_{I\nu}(k,s_2) = -g_{\mu\nu} + \frac{k_\mu k_\nu}{m^2}$$

光锥di-夸克模型中核子电磁形状因子零模的研究

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日期：2022年6月20日

文献：J. Phys. G 32 (2006) 189–201

◆研究动机

◆研究方法

◆数值结果

INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **32** (2006) 189–201 — doi:10.1088/0954-3899/32/2/010

Zero modes in electromagnetic form factors of the nucleon in a light-cone diquark model

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文献： J. Phys. G 32 (2006) 189–201

研究动机

1. 直接用相对论形式计算所有阶的相对论贡献，可以避免v/c或p/m幂次展开的截断。

2. 光锥夸克模型（LC QM）可应用于研究介子电弱特性，同时di-夸克模型也广泛应用于重子性质的研究。

3. 在以前所有重子性质的研究中，人们都没有考虑零模（zero mode）贡献。

研究方法:光锥di-夸克模型（LC dQM）

一、费曼图及di-夸克费曼规则

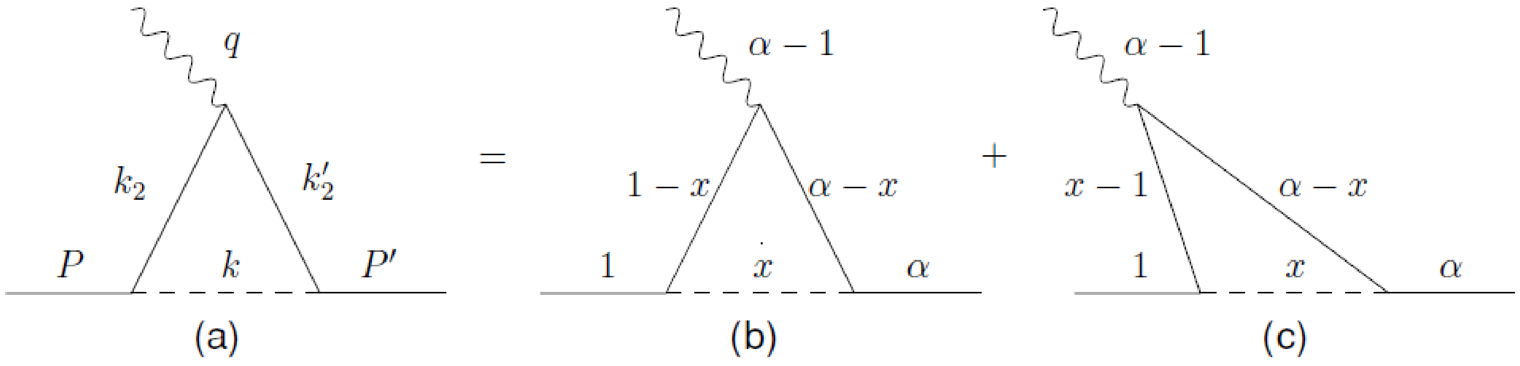

Figure 1. Feynman diagrams for the nucleon current in case a photon strikes the quark. The case of a photon striking the diquark is analogous.

Table 1. Feynman rules of the diquark.

S	V	SqN	VqN	$S\gamma S$	$V\gamma V$
$\frac{\iota}{p^2-m_S^2}$	$-\frac{\iota\delta_{ij}g_{\alpha\beta}}{p^2-m_V^2}$	ιf_S	$f_V\mathcal{O}_V^\alpha\frac{\tau^i}{\sqrt{3}}$	$\frac{1}{3}\Gamma_S^\mu$	$\mathrm{Tr}[\tau_i e_q\tau_j]\Gamma_{V\alpha\beta}^\mu$

$$\Gamma_S^\mu = -\iota(p_1+p_2)^\mu,$$

$$\Gamma_{V\alpha\beta}^\mu = \iota\left\{g_{\alpha\beta}(p_1+p_2)^\mu - (1+\kappa)g_\alpha^\mu(p_1-p_2)_\beta - (1+\kappa)g_\beta^\mu(p_2-p_1)_\alpha\right\},$$

研究方法

二、重子电磁形状因子定义

$$\langle N\lambda'|J^{\mu}|N\lambda\rangle = -\imath e\bar{u}_{\lambda'}(P')\left[\gamma^{\mu}F_1(q^2) + \frac{1}{4m_{\rm N}}q_{\nu}[\gamma^{\nu},\gamma^{\mu}]F_2(q^2)\right]u_{\lambda}(P), \quad (10)$$

电四偶极子和磁偶极子

$$G_{\rm E}(q^2) = F_1(q^2) + \frac{q^2}{4m_{\rm N}^2}F_2(q^2), \qquad G_{\rm M}(q^2) = F_1(q^2) + F_2(q^2).$$

文献：J. Phys. G 32 (2006) 189–201

研究方法

三、计算矩阵元

$$J^{+}_{\lambda\lambda'} = \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \frac{\Lambda(k_2')S^{+}_{\lambda\lambda'}\Lambda(k_2)}{D(k_2')D(k)D(k_2)},$$

I　光子撞击夸克

$$S^{\mu}_{\mathrm{qS}} = -\imath\langle f|[k_2']e_{\mathrm{q}}\gamma^{\mu}[k_2]|i\rangle,$$

$$S^{\mu}_{\mathrm{qV}} = \imath\delta_{ij}g_{\alpha\beta}\langle f|\bar{\mathcal{O}}^{\alpha}_{\mathrm{V}}\frac{\tau^{i\dagger}}{\sqrt{3}}[k_2']e_{\mathrm{q}}\gamma^{\mu}[k_2]\mathcal{O}^{\beta}_{\mathrm{V}}\frac{\tau^{j}}{\sqrt{3}}|i$$

II　光子撞击di-夸克

$$S^{\mu}_{\mathrm{DS}} = \langle f|[k]|i\rangle\frac{1}{3}\Gamma^{\mu}_{\mathrm{S}},$$

$$S^{\mu}_{\mathrm{DV}} = \langle f|\bar{\mathcal{O}}^{\alpha}_{\mathrm{V}}\frac{\tau^{i\dagger}}{\sqrt{3}}[k]\mathcal{O}^{\beta}_{\mathrm{V}}\frac{\tau^{j}}{\sqrt{3}}|i\rangle\mathrm{Tr}[\tau_i e_{\mathrm{q}}\tau_j]\Gamma^{\mu}_{V\alpha\beta},$$

其中: $[p] = \gamma\cdot p + m,$　　$\varphi(x_2, \boldsymbol{k}_{2\perp}) = \frac{1}{\sqrt{2(2\pi)^3}}\frac{\Lambda^2}{(m_{\mathrm{N}}^2 - M_0^2)x_2(m_{\mathrm{N}}^2 - M_{\Lambda}^2)},$

数值结果

I 高斯波函数

$$\varphi(x, k_\perp) = N \exp\left(-M_0^2/8\beta^2\right)$$

II 负幂次波函数

$$\varphi(x, k_\perp) = N\left(\omega^2 + M_0^2\right)^{-3.5},$$

输入参数：

Table 2. Parameters for Gaussian-type wavefunction (Gau) and for negative power one (NP).

	m_q (MeV)	m_D (MeV)	κ	β (MeV)	ω (MeV)
Gau	313	626	1.6	225	–
NP	313	626	1.6	–	100

数值结果

Table 3. Charge and magnetic radii and magnetic moments for different values of f_V. The data are from [33–36].

	f_V (MeV)	r_C^p (fm)	r_M^p (fm)	r_C^{2n} (fm^2)	r_M^n (fm)	$\mu_p(\mu_N)$	$\mu_n(\mu_N)$
Gau I	80	0.804	0.834	−0.262	0.861	2.225	−1.009
NP I	80	0.821	0.855	−0.274	0.882	2.228	−1.013
Gau II	100	0.821	0.820	−0.284	0.850	2.427	−1.075
NP II	100	0.836	0.837	−0.295	0.868	2.428	−1.078
Gau III	130	0.854	0.796	−0.325	0.832	2.814	−1.201
NP III	130	0.872	0.816	−0.339	0.852	2.811	−1.203
Experimental	–	0.870 (8)	0.855 (35)	−0.116 (2)	0.873 (11)	2.793	−1.913

数值结果

$$G_E^p(Q^2) = G_M^p(Q^2)/\mu_p = G_M^n(Q^2)/\mu_n = F_D(Q^2) = \left(1 + \frac{Q^2}{m_D^2}\right)^{-2},$$

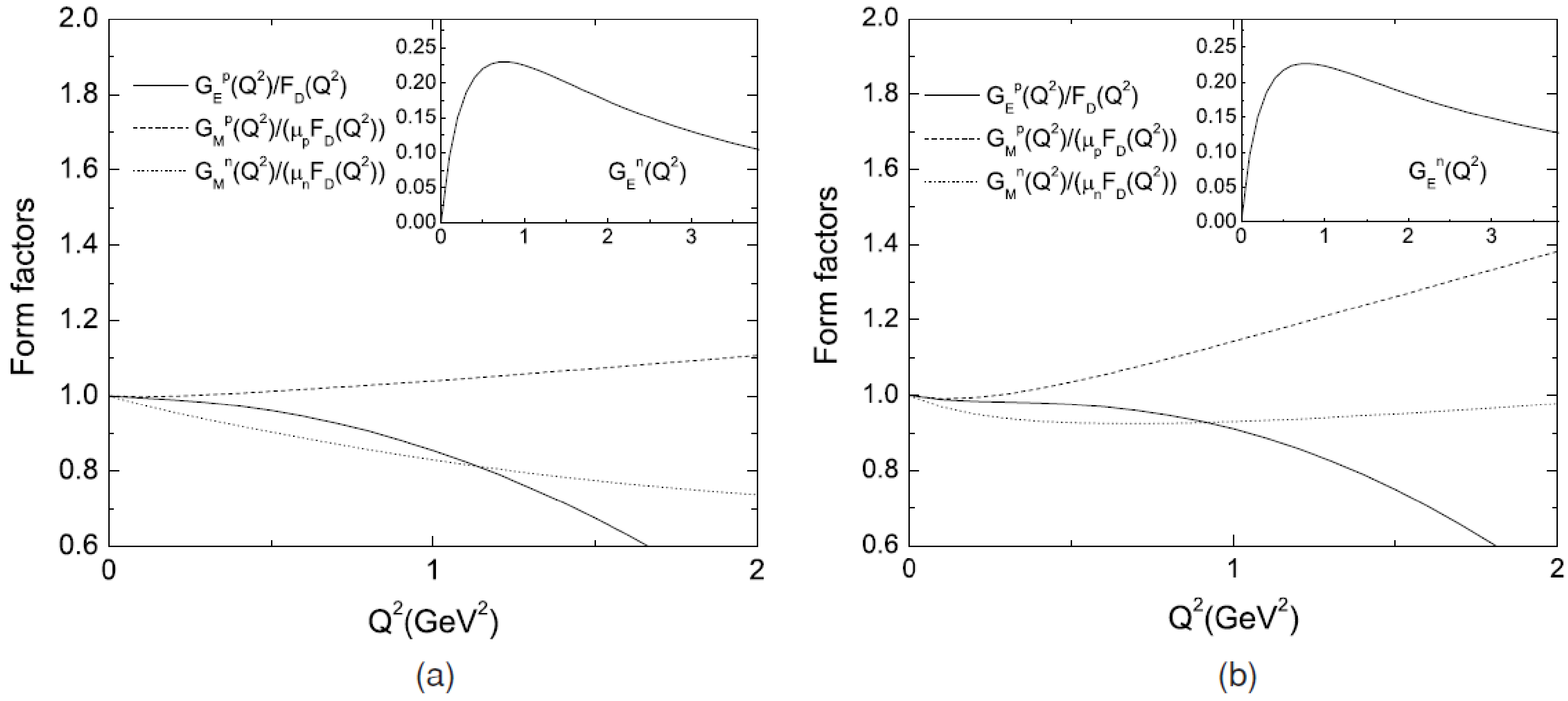

Figure 3. Form factors of the nucleon. Panels (a) and (b) are for the Gaussian-type and negative-power-type wavefunctions with $f_V = 100$ MeV, respectively.

谢谢！

研究方法

二、核子波函数(NJL model)

$$|N\rangle = f_S \varphi_S(x, k_\perp) \overline{u}(k) \mathcal{O}_S u_\lambda(P) + f_V \varphi_V(x, k_\perp) \epsilon_\alpha^i \overline{u}(k) \mathcal{O}_V^\alpha \frac{\tau^i}{\sqrt{3}} u_\lambda(P), \tag{4}$$

$$\mathcal{O}_S = 1, \qquad \mathcal{O}_V^\alpha = (\gamma^\alpha + P^\alpha / M)\gamma_5, \tag{5}$$

φ_S: 标量di − 夸克波函数

φ_V: 轴矢量di − 夸克波函数

$f_{S(V)}$: 标量（轴矢量）耦合常数

文献：J. Phys. G 32 (2006) 189–201