光前夸克模型下重子Ξ_c'半轻衰变的计算

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研究动机

- $M_{\Xi_c'^+} - M_{\Xi_c^+} = 2578.4 - 2467.94 = 110.46 MeV < 139.57(M_\pi)$，由辐射衰变$\Xi_c' \to \Xi_c\gamma$主导，弱衰变是非常稀有的。

- 探究重子内部结构，检测标准模型及找寻可能存在的新物理。

- 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。

$\mathcal{B}(1/2) \to \mathcal{B}(1/2)$ 弱衰变形状因子

定义：

$$\left\langle \mathcal{B}'\left(P', J_z'\right)\left|\bar{q}\gamma_\mu Q\right|\mathcal{B}\left(P, J_z\right)\right\rangle = \bar{u}\left(P', J_z'\right)\left[f_1^V\left(q^2\right)\gamma_\mu + i\frac{f_2^V\left(q^2\right)}{M+M'}\sigma_{\mu\nu}q^\nu + \frac{f_3^V\left(q^2\right)}{M+M'}q_\mu\right]u\left(P, J_z\right), \tag{1}$$

$$\left\langle \mathcal{B}'\left(P', J_z'\right)\left|\bar{q}\gamma_\mu\gamma_5 Q\right|\mathcal{B}\left(P, J_z\right)\right\rangle = \bar{u}\left(P', J_z'\right)\left[g_1^A\left(q^2\right)\gamma_\mu + i\frac{g_2^A\left(q^2\right)}{M-M'}\sigma_{\mu\nu}q^\nu + \frac{g_3^A\left(q^2\right)}{M-M'}q_\mu\right]\gamma_5 u\left(P, J_z\right), \tag{2}$$

对形状因子作类时空间延拓，选用参数化模型为，

$$F\left(q^2\right) = \frac{F(0)}{\left(1-q^2/M_{pole}^2\right)\left[1-a\left(q^2/M_{pole}^2\right)+b\left(q^2/M_{pole}^2\right)^2\right]}. \tag{3}$$

形状因子理论结果

$$f_1^V\left(q^2\right) = \int \frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3} \frac{\phi'^*_{nL'}\left(x',k'_\perp\right)\phi_{1L}\left(x,k_\perp\right)}{16xP^+P'^+\sqrt{\left(k'_1\cdot\bar{P}'+m'_1M'_0\right)\left(k_1\cdot\bar{P}+m_1M_0\right)}} \times \mathrm{Tr}\left[\left(\bar{\not{P}}+M_0\right)\gamma^+\left(\bar{\not{P}}'+M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}'_1+m'_1\right)\gamma^+\left(\not{k}_1+m_1\right)\Gamma_{LS_{[qq]}J_l}\right], \tag{4}$$

$$f_2^V\left(q^2\right) = \frac{-i(M+M')q^i_\perp}{\mathbf{q}^2_\perp}\int \frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3} \frac{\phi'^*_{nL'}\left(x',k'_\perp\right)\phi_{1L}\left(x,k_\perp\right)}{16xP^+P'^+\sqrt{\left(k'_1\cdot\bar{P}'+m'_1M'_0\right)\left(k_1\cdot\bar{P}+m_1M_0\right)}} \times \mathrm{Tr}\left[\left(\bar{\not{P}}+M_0\right)\sigma^{i+}\left(\bar{\not{P}}'+M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}'_1+m'_1\right)\gamma^+\left(\not{k}_1+m_1\right)\Gamma_{LS_{[qq]}J_l}\right], \tag{5}$$

$$g_1^A\left(q^2\right) = \int \frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3} \frac{\phi'^*_{nL'}\left(x',k'_\perp\right)\phi_{1L}\left(x,k_\perp\right)}{16xP^+P'^+\sqrt{\left(k'_1\cdot\bar{P}'+m'_1M'_0\right)\left(k_1\cdot\bar{P}+m_1M_0\right)}} \times \mathrm{Tr}\left[\left(\bar{\not{P}}+M_0\right)\gamma^+\gamma_5\left(\bar{\not{P}}'+M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}'_1+m'_1\right)\gamma^+\gamma_5\left(\not{k}_1+m_1\right)\Gamma_{LS_{[qq]}J_l}\right], \tag{6}$$

$$g_2^A\left(q^2\right) = \frac{i(M-M')\mathbf{q}^i_\perp}{\mathbf{q}^2_\perp}\int \frac{dxd^2\mathbf{k}_\perp}{2(2\pi)^3} \frac{\phi'^*_{nL'}\left(x',k'_\perp\right)\phi_{1L}\left(x,k_\perp\right)}{16xP^+P'^+\sqrt{\left(k'_1\cdot\bar{P}'+m'_1M'_0\right)\left(k_1\cdot\bar{P}+m_1M_0\right)}} \times \mathrm{Tr}\left[\left(\bar{P}+M_0\right)\sigma^{i+}\gamma_5\left(\bar{P}'+M'_0\right)\bar{\Gamma}_{L'S_{[qq]}J'_l}\left(\not{k}'_1+m'_1\right)\gamma^+\gamma_5\left(\not{k}_1+m_1\right)\Gamma_{LS_{[qq]}J_l}\right], \tag{7}$$

味道自旋波函数

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[3]，

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

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，

$$\left\langle\mathcal{B}'\left|j_\mu\right|\mathcal{B}\right\rangle=c_S\left\langle q_1\left[q_2 q_3\right]_S\left|j_\mu\right| q_1\left[q_2 q_3\right]_S\right\rangle+c_A\left\langle q_1\left[q_2 q_3\right]_A\left|j_\mu\right| q_1\left[q_2 q_3\right]_A\right\rangle .$$

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

$$\Lambda=\frac{1}{2\sqrt{6}}\left(\sqrt{3}d(us)_A+\sqrt{3}d(su)_A-\sqrt{3}u(ds)_A-\sqrt{3}u(sd)_A\right.$$
$$\left.+2s(ud)_S-2s(du)_S+d(us)_S-d(su)_S-u(ds)_S+u(sd)_S\right).$$

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

$$\Sigma^0=\frac{1}{2\sqrt{6}}\left(2s(ud)_A+2s(du)_A-d(us)_A-d(su)_A-u(ds)_A-u(s\right.$$
$$\left.+\sqrt{3}u(ds)_S-\sqrt{3}u(sd)_S+\sqrt{3}d(us)_S-\sqrt{3}d(su)_S\right),$$

对于$\mathcal{B}_{q_1 q_1 q_2}\left(\Sigma^-\ (q_1,q_2)=(d,s),\ \Xi^{0,-}(q_1,q_2)=(s,u),(s,d)\right)$，则有

$$\mathcal{B}_{q_1 q_1 q_2}=\frac{1}{2\sqrt{3}}\left(-q_1\left(q_1 q_2\right)_A-q_1\left(q_2 q_1\right)_A+2q_2\left(q_1 q_1\right)_A+\sqrt{3}q_1\left(q_1 q_2\right)_S-\sqrt{3}q_1\left(q_2 q_1\right)_S\right).$$

- $\Xi_c^+\to\Lambda,\Sigma^0,\Xi^0,\quad c_S=\frac{1}{2\sqrt{3}},\frac{1}{2},-\frac{1}{\sqrt{2}};c_A=0.$
- $\Xi_c^0\to\Sigma^-,\Xi^-,\quad c_S=\frac{1}{\sqrt{2}},-\frac{1}{\sqrt{2}};c_A=0.$
- $\Xi_c^{\prime 0}\to\Lambda,\Sigma^0,\Xi^0,\quad c_S=0;c_A=-\frac{1}{2},\frac{1}{2\sqrt{3}},\frac{1}{\sqrt{6}}.$
- $\Xi_c^{\prime 0}\to\Sigma^-,\Xi^-,\quad c_S=0;c_A=\frac{1}{\sqrt{6}},\frac{1}{\sqrt{6}}.$

重子半轻衰变

有效电弱哈密顿量写为:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \Big(V_{cs}^* \left[\bar{s}\gamma_\mu \left(1-\gamma_5\right) c\right] \left[\bar{v}\gamma^\mu \left(1-\gamma_5\right) l\right] + V_{cd}^* \left[\bar{d}\gamma_\mu \left(1-\gamma_5\right) c\right] \left[\bar{v}\gamma^\mu \left(1-\gamma_5\right) l\right] \Big) \tag{8}$$

半轻过程微分衰变宽度:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{\mathrm{d}\Gamma_L}{\mathrm{d}q^2} + \frac{\mathrm{d}\Gamma_T}{\mathrm{d}q^2}. \tag{9}$$

其中,

$$\frac{d\Gamma_L}{dq^2} = \frac{G_F^2 |V_{CKM}|^2}{(2\pi)^3} \frac{q^2 |\vec{P}'|}{24M^2} \left(\left| H_{\frac{1}{2},0} \right|^2 + \left| H_{-\frac{1}{2},0} \right|^2 \right), \qquad \frac{d\Gamma_T}{dq^2} = \frac{G_F^2 |V_{CKM}|^2}{(2\pi)^3} \frac{q^2 |\vec{P}'|}{24M^2} \left(\left| H_{\frac{1}{2},1} \right|^2 + \left| H_{-\frac{1}{2},-1} \right|^2 \right).$$

$|\vec{P}'| = \sqrt{Q_+ Q_-}/2M$,$Q_\pm = 2\left(P \cdot P' \pm MM'\right) = \left(M \pm M'\right)^2 - q^2$,这里轻子质量忽略不计,即$l = e, \mu$。

螺旋度振幅 [1]:

$$H^V_{\frac{1}{2},0} = -i\frac{\sqrt{Q_-}}{\sqrt{q^2}}\left(\left(M+M'\right)f_1 - \frac{q^2}{M+M'}f_2\right) = H^V_{-\frac{1}{2},0}, \tag{10}$$

$$H^V_{\frac{1}{2},1} = i\sqrt{2Q_-}\left(-f_1+f_2\right) = H^V_{-\frac{1}{2},-1}, \tag{11}$$

$$H^A_{\frac{1}{2},0} = -i\frac{\sqrt{Q_+}}{\sqrt{q^2}}\left(\left(M-M'\right)g_1 + \frac{q^2}{M-M'}g_2\right) = -H^A_{-\frac{1}{2},0}, \tag{12}$$

$$H^A_{\frac{1}{2},1} = i\sqrt{2Q_+}\left(-g_1-g_2\right) = -H^A_{-\frac{1}{2},-1}. \tag{13}$$

输入参数 [2,3]

Table 1: Masses of baryons (in units of GeV).

baryon	Λ	Σ^+	Σ^0	Ξ^+	Ξ^0	Ξ_c^+	Ξ_c^0	$\Xi_c^{\prime +}$	$\Xi_c^{\prime 0}$
mass	1.116	1.197	1.193	1.322	1.315	2.468	2.470	2.578	2.579

Table 2: The values of Gaussian parameters β and the di-quark masses,$q = u, d$ (in units of GeV).

di-quark	$\beta_{q[sq]}$	$\beta_{s[sq]}$	$\beta_{c[sq]}$	$m_{[sq]}$
S	0.41	0.46	0.58	0.60
A	0.37	0.44	0.54	0.87

组分夸克质量:

$m_q = 0.25\text{GeV}, \quad m_s = 0.37\text{GeV}, \quad m_c = 1.4\text{GeV}.$

费米常数和CKM 矩阵元:

$G_F = 1.167 \times 10^{-5}\text{GeV}^{-2}, |V_{cd}| = 0.225, \quad |V_{cs}| = 0.974,$

$\tau_{\Xi_c^+} = 4.53 \times 10^{-13}s, \quad \tau_{\Xi_c^0} = 1.52 \times 10^{-13}s.$

形状因子数值结果

Table 3: The transition form factors of Ξ_c with scalar (0^+) diquarks.

	F	$F(0)$	a	b	F	$F(0)$	a	b
$\Xi_c \to \Lambda$	f_1	0.72	-0.14	0.14	g_1	0.61	-0.33	0.24
	f_2	-0.61	0.23	0.06	g_2	-0.03	0.61	0.08
$\Xi_c \to \Sigma$	f_1	0.72	-0.12	0.12	g_1	0.61	-0.33	0.25
	f_2	-0.63	0.23	0.07	g_2	-0.03	0.81	0.18
$\Xi_c \to \Xi$	f_1	0.80	-0.14	0.14	g_1	0.69	-0.34	0.28
	f_2	-0.66	0.22	0.07	g_2	-0.03	0.61	0.08

Table 4: The transition form factors of Ξ_c' with the axial vector (1^+) diquarks.

	F	$F(0)$	a	b	F	$F(0)$	a	b
$\Xi_c' \to \Lambda$	f_1	0.62	-0.81	0.77	g_1	-0.18	0.24	-0.47
	f_2	0.90	-0.13	0.43	g_2	0.02	2.02	7.35
$\Xi_c' \to \Sigma$	f_1	0.62	-0.83	0.83	g_1	-0.18	0.26	-0.51
	f_2	0.92	-0.14	0.45	g_2	0.02	2.22	7.29
$\Xi_c' \to \Xi$	f_1	0.74	-0.87	0.93	g_1	-0.22	0.10	-0.48
	f_2	1.08	-0.18	0.47	g_2	0.02	1.81	8.93

形状因子

Figure 1: The q^2 dependence of transition form factors of Ξ_c with the scalar (0^+) diquarks.

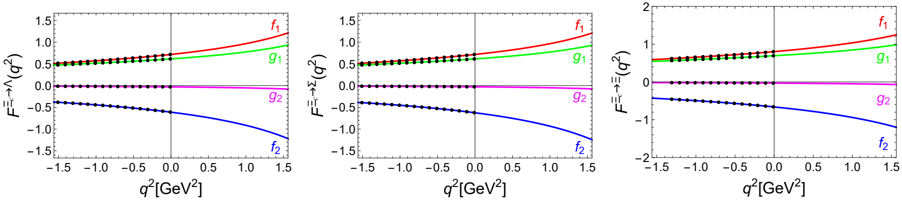
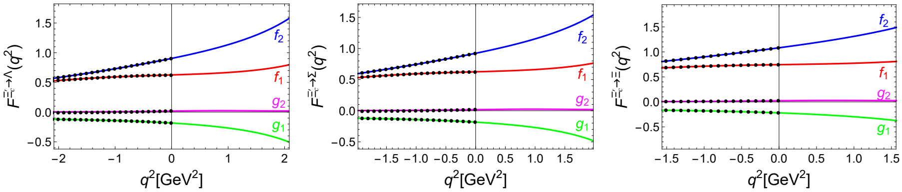


Figure 2: The q^2 dependence of transition form factors of Ξ_c' with the axial vector (1^+) diquarks.



Ξ_c 和Ξ'_c 半轻衰变数值结果

Table 5: Decay widths of $\Gamma(\Xi_c'^{(+,0)} \to \Xi_c^{(+,0)}\gamma)$ transitions(in units of keV).

	LQCD [4]	HHCPT [5]	LCQCD SR [6]	LC SR [7]	RTQM [8]	HHCPT [9]
$\Gamma(\Xi_c'^{+} \to \Xi_c^{+}\gamma)$	5.468	5.43	0.700	8.50	12.70	54.31
$\Gamma(\Xi_c'^{0} \to \Xi_c^{0}\gamma)$	0.002	0.46	0.002	0.27	0.17	0.02

Table 6: Semi-leptonic decays for charmed baryons Ξ_c.

channels	Γ(GeV)	$\mathcal{B}$	Γ_L/Γ_T
$\Xi_c^+ \to \Lambda l^+ \nu_l$	1.30×10^{-15}	8.98×10^{-4}	1.71
$\Xi_c^+ \to \Sigma^0 l^+ \nu_l$	2.90×10^{-15}	2.01×10^{-3}	1.80
$\Xi_c^+ \to \Xi^0 l^+ \nu_l$	8.12×10^{-14}	8.12×10^{-2}	1.92
$\Xi_c^0 \to \Sigma^- l^+ \nu_l$	6.93×10^{-15}	1.61×10^{-3}	1.83
$\Xi_c^0 \to \Xi^- l^+ \nu_l$	8.00×10^{-14}	1.86×10^{-2}	1.93

Table 7: Semi-leptonic decays for charmed baryons Ξ'_c, we choose numerical results for $\Gamma(\Xi'_c \to \Xi_c\gamma)$ in the LQCD.

channels	Γ(GeV)	$\mathcal{B}$	Γ_L/Γ_T
$\Xi_c'^+ \to \Lambda l^+ \nu_l$	1.28×10^{-15}	2.35×10^{-10}	3.78
$\Xi_c'^+ \to \Sigma^0 l^+ \nu_l$	3.33×10^{-16}	6.08×10^{-11}	4.30
$\Xi_c'^+ \to \Xi^0 l^+ \nu_l$	1.14×10^{-14}	2.08×10^{-9}	5.82
$\Xi_c'^0 \to \Sigma^- l^+ \nu_l$	6.57×10^{-16}	3.29×10^{-7}	4.29
$\Xi_c'^0 \to \Xi^- l^+ \nu_l$	1.12×10^{-14}	5.59×10^{-6}	5.87

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谢谢!