第 25 卷 第 12 期 高能物理与核物理 Vol.25, No.12
2001 年 12 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Dec., 2001

动力学破缺和真空自发破缺的手征 $SU(2)_L \times SU(2)_R \times U(1)\sigma$ 模型

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摘要 将 $SU(2)_L \times SU(2)_R$ 手征对称的 σ 模型推广到带电磁场情况下的手征 σ 模型,采用研究自恰性方程的方法研究了同时具有动力学破缺和真空自发破缺的手征 $SU(2)_L \times SU(2)_R \times U(1)\sigma$ 模型,得到了考虑动力学自发破缺、真空自发破缺和电磁相互作用后,σ、π 介子和核子都出现了不同的质量修正,并得到此模型中 σ,π 和核子以不同方式依赖于动力学破缺的具体表示.

关键词 动力学破缺 真空自发破缺 σ 模型 手征对称 Higgs 机制

1 引言

Higgs 机制在解释一些粒子获得质量方面取得了巨大的成功,但是到目前为止,尽管探测 Higgs 粒子的能量不断提高,已把 Higgs 粒子的质量下限提高到 95.1GeV,可是还没有发现 Higgs 粒子[1],以及标准模型的自由参数太多[2],导致人为的调节太多,使理论的预言性降低,促使人们探索多种质量产生机制[3—5]. 动力学破缺产生质量便是其中之一,它不但使自由调节参数大大减少,而且可给出不同于 Higgs 机制的质量产生[6].

$SU(2)_L \times SU(2)_R\ \sigma$ 模型[7]是研究手征对称性破缺的经典模型. 此模型的最大特点是同时存在两种类型对称性的破缺:一种是由标量场的真空期望值不为零所引发的破缺;另一种是由正反费米子对所形成的束缚态的真空期望值不为零所引发的破缺[8]. 我们一般地研究带有电磁场的情况,考虑 π 介子和核子与电磁场存在相互作用的 $SU(2)_L \times SU(2)_R \times U(1)\sigma$ 模型,讨论选择不同破缺方向时,σ 和 π 介子以及费米子的质量问题.

研究自恰性方程[9]可以作为研究真空自发破缺的一个有效途径. 下面首先导出相应的自恰性方程.

2 自恰性方程

具有 $SU(2)_L \times SU(2)_R$ 手征对称和电磁相互作用 $U(1)$ 对称的 σ 模型的拉氏量为

2001－03－12 收稿

$$\mathscr{L}=-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\bar{\psi}(x)\gamma^{\mu}[\partial_{\mu}-\mathrm{i}eA_{\mu}]\psi(x)-g\bar{\psi}(x)[\sigma(x)+\mathrm{i}\boldsymbol{\tau}\cdot\boldsymbol{\pi}(x)\gamma_5]\psi(x)-\frac{1}{2}(\partial_{\mu}\sigma(x))^2-\frac{1}{2}(D_{\mu}\boldsymbol{\pi}(x))^{+}\cdot(D_{\mu}\boldsymbol{\pi}(x))-\frac{\lambda}{4}[\sigma^2(x)+\boldsymbol{\pi}^2(x)-\nu^2]^2,\tag{1}$$

其中 $\boldsymbol{\tau}$ 为泡利矩阵,核子场 $\psi(x)=\begin{bmatrix}\psi_p(x)\\ \psi_n(x)\end{bmatrix}$是同位旋二重态,$\sigma(x)$是同位旋为零的标量场,$\boldsymbol{\pi}(x)$是同位旋为 1 的赝标量场,$F_{\mu\nu}=\partial_{\mu}A_{\nu}-\partial_{\nu}A_{\mu}$ 为电磁场场强以及 $D_{\mu}=\partial_{\mu}-\mathrm{i}eA_{\mu}$ 为协变微商. 且 $\boldsymbol{\pi}(x)^{+}=\boldsymbol{\pi}(x)$[10].

考虑外源存在的拉氏量为

$$\mathscr{L}_J=\mathscr{L}+\bar{\eta}\psi+\bar{\psi}\eta+J_{\sigma}\sigma+\boldsymbol{J}_{\pi}\cdot\boldsymbol{\pi}+J_{A_{\mu}}A_{\mu},\tag{2}$$

其中 $J=(\bar{\eta},\eta,J_{\sigma},\boldsymbol{J}_{\pi},J_{A_{\mu}})$,则相应的运动方程为

$$[\gamma^{\mu}\partial_{\mu}-\mathrm{i}e\gamma^{\mu}A_{\mu}+g(\sigma(x)+\mathrm{i}\boldsymbol{\tau}\cdot\boldsymbol{\pi}(x)\gamma_5)]\psi(x)=\eta(x),\tag{3}$$

$$\bar{\psi}(x)[-\gamma^{\mu}\overleftarrow{\partial}_{\mu}-\mathrm{i}e\gamma^{\mu}A_{\mu}+g(\sigma(x)+\mathrm{i}\boldsymbol{\tau}\cdot\boldsymbol{\pi}(x)\gamma_5)]=\bar{\eta}(x),\tag{4}$$

$$(\Box+\lambda\nu^2)\sigma(x)=g\bar{\psi}(x)\psi(x)+\lambda\sigma(x)(\sigma^2(x)+\boldsymbol{\pi}^2(x))-J_{\sigma}(x),\tag{5}$$

$$(\partial^{\mu}\partial_{\mu}^{*}+\lambda\nu^2)\boldsymbol{\pi}(x)=e^2A_{\mu}^2\boldsymbol{\pi}(x)+g\bar{\psi}(x)\mathrm{i}\boldsymbol{\tau}\gamma_5\psi(x)+\lambda\boldsymbol{\pi}(x)(\sigma^2(x)+\boldsymbol{\pi}^2(x))-\boldsymbol{J}_{\pi}(x),\tag{6}$$

$$\partial_{\nu}F^{\mu\nu}+\mathrm{i}e\bar{\psi}(x)\gamma^{\mu}\psi(x)-e^2A_{\mu}(x)\boldsymbol{\pi}^2(x)=-J_{A_{\mu}}(x).\tag{7}$$

关于方程(6),只要将$\partial^{\mu}\partial_{\mu}^{*}$作一个变换就可得算符“□”,故又可按通常方式求解. 将(5)—(7)式两边对真空求平均,有

$$(\Box+\lambda\nu^2)\langle\sigma(x)\rangle_0^J=g\langle\bar{\psi}(x)\psi(x)\rangle_0^J+\lambda\langle\sigma(x)(\sigma^2(x)+\boldsymbol{\pi}^2(x))\rangle_0^J-J_{\sigma}(x),\tag{8}$$

$$(\partial^{\mu}\partial_{\mu}^{*}+\lambda\nu^2)\langle\boldsymbol{\pi}(x)\rangle_0^J=e^2\langle A_{\mu}^2\boldsymbol{\pi}(x)\rangle_0^J+g\langle\bar{\psi}(x)\mathrm{i}\boldsymbol{\tau}\gamma_5\psi(x)\rangle_0^J+\lambda\langle\boldsymbol{\pi}(x)(\sigma^2(x)+\boldsymbol{\pi}^2(x))\rangle_0^J-\boldsymbol{J}_{\pi}(x),\tag{9}$$

$$-e\langle j^{\mu}\rangle_0^J=-\mathrm{i}e\langle\bar{\psi}(x)\gamma^{\mu}\psi(x)\rangle_0^J+e^2\langle A_{\mu}(x)\boldsymbol{\pi}^2(x)\rangle_0^J-J_{A_{\mu}}(x),\tag{10}$$

且$\langle B(x)\rangle_0^J\equiv\langle 0_{out}|B(x)|0_{in}\rangle^J/\langle 0_{out}|0_{in}\rangle^J$.

体系的生成泛函为

$$Z(J)\equiv\int[D\bar{\psi}][D\psi][D\sigma][D\boldsymbol{\pi}][DA_{\mu}]\exp\left(\frac{\mathrm{i}}{\hbar}\int\mathrm{d}^4x\mathscr{L}_J\right),\tag{11}$$

故场的平均值又可以表示为

$$\langle B(x)\rangle_0^J=\hbar\delta W/\delta J_B(x),\quad(Z=e^{\mathrm{i}W}),\tag{12}$$

按照场的平均值的展开有

$$\langle\sigma^3(x)\rangle_0^J=(\langle\sigma(x)\rangle_0^J)^3+3\frac{\hbar}{\mathrm{i}}\langle\sigma(x)\rangle_0^J\frac{\delta\langle\sigma(x)\rangle_0^J}{\delta J_{\sigma}(x)}+\left(\frac{\hbar}{\mathrm{i}}\right)^2\frac{\delta^2\langle\sigma(x)\rangle_0^J}{\delta J_{\sigma}(x)\delta J_{\sigma}(x)}+\cdots,\tag{13}$$

$$\langle\sigma(x)\boldsymbol{\pi}^2(x)\rangle_0^J=(\langle\boldsymbol{\pi}(x)\rangle_0^J)^2\langle\sigma(x)\rangle_0^J+\frac{\hbar}{\mathrm{i}}\langle\sigma(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta\boldsymbol{J}_{\pi}(x)}+$$

$$2\frac{\hbar}{i}\langle\boldsymbol{\pi}(x)\rangle_0^J\cdot\frac{\delta\langle\sigma(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}+\left(\frac{\hbar}{i}\right)^2\frac{\delta^2\langle\sigma(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)\cdot\delta\boldsymbol{J}_\pi(x)}+\cdots, \tag{14}$$

$$\langle\boldsymbol{\pi}(x)A_\mu^2(x)\rangle_0^J=(\langle A_\mu(x)\rangle_0^J)^2\langle\boldsymbol{\pi}(x)\rangle_0^J+\frac{\hbar}{i}\langle\boldsymbol{\pi}(x)\rangle_0^J\frac{\delta\langle A_\mu(x)\rangle_0^J}{\delta J_{A_\mu}(x)}+$$
$$2\frac{\hbar}{i}\langle A_\mu(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta J_{A_\mu}(x)}+\left(\frac{\hbar}{i}\right)^2\frac{\delta^2\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta J_{A_\mu}(x)\delta J_{A_\mu}(x)}+\cdots, \tag{15}$$

$$\langle A_\mu(x)\boldsymbol{\pi}^2(x)\rangle_0^J=\langle A_\mu(x)\rangle_0^J(\langle\boldsymbol{\pi}(x)\rangle_0^J)^2+\frac{\hbar}{i}\langle A_\mu(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}+$$
$$2\frac{\hbar}{i}\langle\boldsymbol{\pi}(x)\rangle_0^J\cdot\frac{\delta\langle A_\mu(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}+\left(\frac{\hbar}{i}\right)^2\frac{\delta^2\langle A_\mu(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)\cdot\delta\boldsymbol{J}_\pi(x)}+\cdots, \tag{16}$$

因此

$$(\Box+\lambda\nu^2)\langle\sigma(x)\rangle_0^J=g\langle\overline{\psi}(x)\psi(x)\rangle_0^J+\lambda\langle\sigma(x)\rangle_0^J[(\langle\sigma(x)\rangle_0^J)^2+(\langle\boldsymbol{\pi}(x)\rangle_0^J)^2]+$$
$$\lambda\frac{\hbar}{i}\left[3\langle\sigma(x)\rangle_0^J\frac{\delta\langle\sigma(x)\rangle_0^J}{\delta J_\sigma(x)}+\langle\sigma(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}+\right.$$
$$\left.2\langle\boldsymbol{\pi}(x)\rangle_0^J\cdot\frac{\delta\langle\sigma(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}\right]+\lambda\left(\frac{\hbar}{i}\right)^2\left[\frac{\delta^2\langle\sigma(x)\rangle_0^J}{\delta J_\sigma(x)\delta J_\sigma(x)}+\right.$$
$$\left.\frac{\delta^2\langle\sigma(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)\cdot\delta\boldsymbol{J}_\pi(x)}\right]-J_\sigma(x)+\cdots, \tag{17}$$

$$(\partial^\mu\partial_\mu^*+\lambda\nu^2)\langle\boldsymbol{\pi}(x)\rangle_0^J=g\langle\overline{\psi}(x)i\boldsymbol{\tau}\gamma_5\psi(x)\rangle_0^J+\lambda\langle\boldsymbol{\pi}(x)\rangle_0^J[(\langle\sigma(x)\rangle_0^J)^2+(\langle\boldsymbol{\pi}(x)\rangle_0^J)^2]+$$
$$\lambda\left(\frac{\hbar}{i}\right)\left[3\langle\boldsymbol{\pi}(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}+2\langle\sigma(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta J_\sigma(x)}+\right.$$
$$\left.\langle\boldsymbol{\pi}(x)\rangle_0^J\frac{\delta\langle\sigma(x)\rangle_0^J}{\delta J_\sigma(x)}\right]+\lambda\left(\frac{\hbar}{i}\right)^2\left[\frac{\delta^2\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta J_\sigma(x)\delta J_\sigma(x)}+\frac{\delta^2\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)\delta\boldsymbol{J}_\pi(x)}\right]+$$
$$e^2\left[(\langle A_\mu(x)\rangle_0^J)^2\langle\boldsymbol{\pi}(x)\rangle_0^J+\frac{\hbar}{i}\langle\boldsymbol{\pi}(x)\rangle_0^J\frac{\delta\langle A_\mu(x)\rangle_0^J}{\delta J_{A_\mu}(x)}+\right.$$
$$\left.2\frac{\hbar}{i}\langle A_\mu(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta J_{A_\mu}(x)}+\left(\frac{\hbar}{i}\right)^2\frac{\delta^2\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta J_{A_\mu}(x)\delta J_{A_\mu}(x)}\right]$$
$$\boldsymbol{J}_\pi(x)+\cdots, \tag{18}$$

$$e\langle j_\mu(x)\rangle_0^J=ie\langle\overline{\psi}(x)\gamma^\mu\psi(x)\rangle_0^J+J_{A_\mu}(x)-e^2\left[(\langle\boldsymbol{\pi}(x)\rangle_0^J)^2\langle A_\mu(x)\rangle_0^J+\right.$$
$$\frac{\hbar}{i}\langle A_\mu(x)\rangle_0^J\frac{\delta\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}+2\frac{\hbar}{i}\langle\boldsymbol{\pi}(x)\rangle_0^J\frac{\delta\langle A_\mu(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)}+$$
$$\left.\left(\frac{\hbar}{i}\right)^2\frac{\delta^2\langle\boldsymbol{\pi}(x)\rangle_0^J}{\delta\boldsymbol{J}_\pi(x)\cdot\delta\boldsymbol{J}_\pi(x)}+\cdots\right]+J_{A_\mu}(x). \tag{19}$$

在树图近似下,可以忽略 $\hbar$ 的各阶项,并令外源为零. 这样(17)—(19)式可以化为

$$g\langle\overline{\psi}(x)\psi(x)\rangle_0^J\big|_{J=0}+\lambda\sigma_0(\sigma_0^2+\boldsymbol{\pi}_0^2-\nu^2)=0, \tag{20}$$

$$ig\,\mathrm{tr}\gamma_5\boldsymbol{\tau}S_F(0)-\lambda\boldsymbol{\pi}_0(\sigma_0^2+\boldsymbol{\pi}_0^2-\nu^2)=0, \tag{21}$$

$$\langle j^\mu(x)\rangle_0^J\big|_{J=0}=i\langle\overline{\psi}(x)\gamma^\mu\psi(x)\rangle_0^J\big|_{J=0}, \tag{22}$$

其中 $\mathrm{tr}\gamma_5 \boldsymbol{\tau} S_F(0) = -\langle\overline{\psi}(x)\gamma_5\boldsymbol{\tau}\psi(x)\rangle_0^J|_{J=0}$, $\sigma_0 = \langle\sigma(x)\rangle_0^J|_{J=0}$, $\boldsymbol{\pi}_0 = \langle\boldsymbol{\pi}(x)\rangle_0^J|_{J=0}$, σ_0 和 $\boldsymbol{\pi}_0$ 是与动力学破缺和时空相关的常数,关于它们的物理意义我们将在后面讨论.

类似于文献[10]的讨论,其费米子传播子的一般表示为

$$S_F(x-x')^J = \int^{\Lambda}\frac{d^4p}{(2\pi)^4}\frac{-e^{i(x-x')\cdot p}}{\gamma^\mu\cdot p_\mu - ig(\langle\sigma(x)\rangle_0^J + i\boldsymbol{\tau}\cdot\langle\boldsymbol{\pi}(x)\rangle_0^J\gamma_5) - e\gamma^\mu\langle A_\mu(x)\rangle_0^J},$$

其中 Λ 为截断参数. 这样(20)—(23)式确定了相应的自恰性方程组.

3　动力学和真空自发破缺后的质量谱

现在我们在一般的情况下研究自发破缺后的质量谱. 一般而言,当 $\sigma_0 \neq 0$, $\langle\overline{\psi}(x)\psi(x)\rangle_0^J|_{J=0}\neq 0$ 时,有

$$\frac{i\langle\overline{\psi}(x)\gamma_5\boldsymbol{\tau}\psi(x)\rangle_0^J|_{J=0}}{\langle\overline{\psi}(x)\psi(x)\rangle_0^J|_{J=0}} = \frac{\boldsymbol{\pi}_0}{\sigma_0},$$

因此可有

$$\sigma_0 = k\langle\overline{\psi}(x)\psi(x)\rangle_0^J|_{J=0}, \tag{25}$$

$$\boldsymbol{\pi}_0 = ik\langle\overline{\psi}(x)\gamma_5\boldsymbol{\tau}\psi(x)\rangle_0^J|_{J=0}, \tag{26}$$

其中 k 是待定系数,(25)和(26)式表明 σ_0 和 $\boldsymbol{\pi}_0$ 直接来源于费米子的动力学凝聚,这是值得重视的新结论. 另一方面,当 $\lambda^{-1} = \nu^2 - \sigma_0^2 - \boldsymbol{\pi}_0^2$ 时,我们又可获得

$$\sigma_0 = g\langle\overline{\psi}(x)\psi(x)\rangle_0^J|_{J=0}, \tag{27}$$

$$\boldsymbol{\pi}_0 = ig\langle\overline{\psi}(x)\gamma_5\boldsymbol{\tau}\psi(x)\rangle_0^J|_{J=0}, \tag{28}$$

即此时 σ_0 和 $\boldsymbol{\pi}_0$ 可看作费米子凝聚而成,同时由(25)—(28)式可见,k 与耦合常数 g 相关,而且事实上对更一般的情况,(27)和(28)式中的 g 前可有一待定系数 c. 进一步分两种情况进行讨论:

(1) 当 $\sigma_0 = 0, \boldsymbol{\pi}_0 = 0$ 时,由(20)和(21)式得

$$\langle\overline{\psi}(x)\psi(x)\rangle_0^J|_{J=0} = i\langle\overline{\psi}(x)\gamma_5\boldsymbol{\tau}\psi(x)\rangle_0^J|_{J=0} = 0, \tag{29}$$

这时既不会发生真空的自发破缺,又不会发生动力学对称性的破缺. $\sigma(x)$和 $\boldsymbol{\pi}(x)$介子具有相同的质量[11]

$$m_\sigma^2 = m_\pi^2 = -\lambda\nu^2, \tag{30}$$

而费米子 p 和 n 的质量保持为零.

(2) 破缺选在 $\sigma(x)$方向时,即

$$\langle\overline{\psi}(x)\psi(x)\rangle_0^J|_{J=0} \neq 0,\quad \langle\overline{\psi}(x)\gamma_5\boldsymbol{\tau}\psi(x)\rangle_0^J|_{J=0} = 0,$$

则有

$$\boldsymbol{\pi}_0 = 0,\qquad \lambda\sigma_0(\sigma_0^2 - \nu^2) = g\,\mathrm{tr}S_F(0), \tag{32}$$

以 $\sigma(x)$场的真空期望值进行平移

$$\sigma(x)\to\sigma(x)+\sigma_0,$$

平移后的拉格朗日量

$$L=-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\overline{\psi}(x)[\gamma^{\mu}(\partial_{\mu}-\mathrm{i}eA_{\mu})+m_{\mathrm{N}}]\psi(x)-g\overline{\psi}(x)[\sigma(x)+\mathrm{i}\boldsymbol{\tau}\cdot\boldsymbol{\pi}(x)\gamma_5]\psi(x)-\frac{1}{2}(\partial_{\mu}\sigma(x))^2-\frac{1}{2}m_{\sigma}^2\sigma^2(x)-\frac{1}{2}m_{\pi}^2\boldsymbol{\pi}^2(x)-\frac{1}{2}(D_{\mu}^{*}\boldsymbol{\pi}(x))\cdot(D_{\mu}\boldsymbol{\pi}(x))-\frac{\lambda}{4}[\sigma^2(x)+\boldsymbol{\pi}^2(x)]^2-\lambda\sigma_0\sigma(x)(\sigma^2(x)+\boldsymbol{\pi}^2(x))-\lambda\sigma_0(\sigma_0^2-\nu^2)\sigma(x), \tag{34}$$

其中核子质量:

$$m_{\mathrm{N}}=g\sigma_0, \tag{35}$$

$\sigma(x)$和 $\boldsymbol{\pi}(x)$介子的质量分别为

$$m_{\sigma}^2=\lambda(3\sigma_0^2-\nu^2), \tag{36}$$

$$m_{\pi}^2=g\mathrm{tr}S_{\mathrm{F}}(0)/\sigma_0=\lambda(\sigma_0^2-\nu^2), \tag{37}$$

由(35)—(37)式可知,当 σ_0 不表示为动力学凝聚,而只表示为时空相关常数时,即使没有动力学破缺,核子也获得了质量,但 $\boldsymbol{\pi}$ 介子质量为零,而且此时 $\sigma_0^2=\nu^2$,有 $m_{\sigma}^2=2\lambda\sigma_0^2$, $m_{\mathrm{N}}=g\sigma_0$;一般而言,同时存在两种破缺时,$\boldsymbol{\pi}$ 介子获得了质量,$\sigma(x)$与 $\boldsymbol{\pi}(x)$的质量不再相等. 当取这一般的 $\sigma_0'=cg\langle\overline{\psi}(x)\psi(x)\rangle_0^J$ 替换(33)式中的 σ_0 时,重复(33)式以下的讨论,由(23)式和新得到一般的(35),(36)式和 $m_{\pi}^2=\lambda(\sigma_0'^2-\nu^2)$,可见在 σ_0 的激发态的条件下(因为$\sigma'_0|_{J=0}=c\sigma_0$ 为基态),或更简化的,在 A_{μ} 的真空平均值的条件下,其外源可以是电流密度,则其电磁场不但对核子和 $\boldsymbol{\pi}(x)$介子的质量有贡献,而且对 σ 的质量也有贡献. 这是因为可把一般的 σ_0' 看作由正反费米子构成的激发态复合粒子. 本文所讨论的质量产生机制对我们进一步研究夸克、轻子和弱玻色子的质量产生和核子的自旋不完全来自夸克的反常是很有启发的,并将另文给出其讨论. (22)式为荷-流矢量凝聚

$$\langle\rho(x)\rangle_0^J|_{J=0}=-\mathrm{i}\langle j^4\rangle|_{J=0}=\langle\psi^{+}(x)\psi(x)\rangle_0^J|_{J=0}, \tag{38}$$

$$\langle j^i(x)\rangle_0^J|_{J=0}=\mathrm{i}\langle\overline{\psi}(x)\gamma^i\psi(x)\rangle_0^J|_{J=0}, \tag{39}$$

ρ 为荷密度凝聚,j^i 为流密度凝聚. 应用路径积分方法研究的内容将另文更进一步给出.

4 结论

我们把 $SU(2)_{\mathrm{L}}\times SU(2)_{\mathrm{R}}\sigma$ 模型扩展到带电磁场的 $SU(2)_{\mathrm{L}}\times SU(2)_{\mathrm{R}}\times U(1)$的 σ 模型,在一般情况下,发现在考虑了电磁相互作用、真空自发破缺和动力学自发破缺后,σ,$\boldsymbol{\pi}$ 介子和核子都出现了不同的质量修正.

由 $m=g\sigma_0$,即核子的质量来自标量场的真空期望值,而标量场的真空期望值可唯象地看作是正反费米子对凝聚而成的. 那么核子的质量来源可为正反费米子对的凝聚效应,即可为动力学的对称性破缺,而不只是真空的自发破缺. 这可从(25)和(26)式中具体看出,σ_0 和 $\boldsymbol{\pi}_0$ 完全可以用费米子的动力学凝聚的形式表示出来. 即 σ_0 和 $\boldsymbol{\pi}_0$ 本身为动力学破缺的结果,说明这里的 $\sigma(x)$和 $\boldsymbol{\pi}(x)$并非基本的标量场和赝标量场[12],而是几种场的效应. 这也说明了在一定条件下基本场和复合场的等价性.

作者感谢李子平教授关于外源的讨论.

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$SU(2)_L \times SU(2)_R \times U(1)$ σ-Model with Both Dynamical Breaking and Vacuum Spontaneous Symmetry Breaking

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Abstract　The $SU(2)_L \times SU(2)_R$ σ-model was extended to a $SU(2)_L \times SU(2)_R \times U(1)\sigma$-model with electromagnetic interaction. The chiral $SU(2)_L \times SU(2)_R \times U(1)\sigma$-model with both dynamical breaking and vacuum spontaneous symmetry breaking is investigated by means of the Consistent Equation. It is obtained that when considering dynamical breaking and vacuum spontaneous symmetry breaking and electromagnetic interaction in different cases, σ, π and nucleon have different mass amendments, and the concrete representation forms depending on dynamical symmetry breaking in different ways are abtained for the mass generation of σ, π and nucleon. The equivalences of fundamental scalar fields and composed scalar fields are proved. This paper gives a base of constructing the unified weak-electromagnetic model based on dynamical breaking and vacuum spontaneous symmetry breaking.

Key words　dynamical breaking, vacuum spontaneous breaking, σ-model, chiral symmetry, Higgs mechanism

Received 12 March 2001