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WEAK ISOSPIN SPECTROSCOPY OF EXCITED QUARKS AND LEPTONS

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Abstract

We investigate new excited states of quarks and leptons in the light of weak isospin invariance. We find to first order that while quark states with isospin assignment $I_w=0, \frac{1}{2}$ are dominantly decaying strongly, $I_w=1, \frac{3}{2}$ quarks can only decay electroweakly. Decays of higher isospin assignments are permitted only in higher orders. Experimental signatures are considered. Production cross-section and decay branching ratios are given. It is also found that $I_w \geq 1$ quarks, will give rise to "exotic" hadrons, namely mesons of charges $\pm 2e$ and baryons with charge $3e$.

1. The discovery of weak bosons and the measurement of the weak angle θ_w at the CERN $\bar{p}p$ Collider[1,2], have given spectacular confirmation to the $SU(2) \times U(1)$ electroweak theory. In this picture , light fermions (quarks and leptons) are assigned to left handed weak isospin doublets ($I_w=\frac{1}{2}$) and right handed singlets ($I_w=0$), while the gauge fields belong to $I_w=0,1$ isospin multiplets.

Much speculation has been put forward to describe the possibility of new, massive sequential states to quarks, leptons and Intermediate Vector Bosons (IVB's)[3÷7]. The success of the standard model leads naturally to the question : can we use weak isospin to extend the spectrum of the "known" (3 families of) light leptons and quarks? Similar techniques have been very successful in the early days of particle physics in the case of the nucleon (proton and neutron) isodoublet with an interaction assumed to be through the isovector pion field. Much progress was made in low energy spectroscopy simply by using isospin to generate baryon and meson resonances long before one learnt about quarks and gluons. In a similar way, weak isospin I_w can unfold some of the structrure of these hypothetical new fermions, leptons and quarks, without reference to a specific dynamical model of their building blocks (preons). Unlike the pion case, we do not have weak boson beams, and the experimental confirmation of such a structure must necessarily come from the study of allowed decay channels.

We shall now consider the allowed isospin states. Since light fermions have $I_w=0, \frac{1}{2}$, EW bosons have I_w=0,1 and gluons have I_w=0, to lowest order in α only fermionic states with $I_w \leq \frac{3}{2}$ can be excited using the above particles. In Table I we show all such states which can be coupled to the known light fermions through EW boson ($\vec{W}^{\mu}, B^{\mu}$) fields and gluon $G^{\mu a}$ fields. For clarity, we only list the multiplets belonging to the first family. The possibility of excited leptons in connection with anomalous Z_0 radiative decays has been already discussed in ref.3. The extension to excited quarks with $I_w=\frac{1}{2}$ (starks) can be found in ref.4.

In order to calculate in detail production and decays of these excited fermions,we need to discuss the nature of their couplings to light fermions and the gauge fields. Because all the gauge fields carry no hypercharge Y, a given excited multiplet couples (through the gauge field) only to a light multiplet with the same Y. (See Table I). Also the coupling has to be of the anomalous magnetic moment type, for current conservation. The decay modes and reaction cross sections can be calculated using the following effective lagrangian in terms of the transition currents :

$$\mathcal{L}_{eff} = g' B^{\mu} J^{Y}_{\mu} + g \vec{W}^{\mu} \cdot \vec{J}_{\mu} + g_s G^{\mu a} J^{a}_{\mu} \qquad (1)$$

TABLE I

Quantum Numbers (charge Q, hypercharge Y) of excited fermions (belonging to the first family) with $I_w \leqslant \frac{3}{2}$ and their couplings to light fermions with the same Y.

I_w	Excited Leptons				Excited Quarks			
	Multiplet	Q	Y	Coupled to	Multiplet	Q	Y	Coupled to
	E^-	-1	-2	e_R through B^μ	(i) U	$\frac{2}{3}$	$+\frac{4}{3}$	u_R through B^μ and $G^{\mu a}$
					(ii) D	$-\frac{1}{3}$	$-\frac{2}{3}$	d_R through B^μ and $G^{\mu a}$
$\frac{1}{2}$	$\mathcal{E} \equiv \begin{pmatrix} E^0 \\ E^- \end{pmatrix}$	0 -1	-1	$l_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ through $\vec{W}^\mu$ and B^μ	$\Psi \begin{pmatrix} U \\ D \end{pmatrix}$	$\frac{2}{3}$ $-\frac{1}{3}$	$\frac{1}{3}$	$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$ through $\vec{W}^\mu$, B^μ and $G^{\mu a}$
1	$\vec{\mathcal{E}} \equiv \begin{pmatrix} E^0 \\ E^- \\ E^{--} \end{pmatrix}$	0 -1 -2	-2	e_R through $\vec{W}^\mu$	(i) $\vec{U} \begin{pmatrix} U_+ \\ U \\ D \end{pmatrix}$	$\frac{5}{3}$ $\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{4}{3}$	u_R through $\vec{W}^\mu$
					(ii) $\vec{D} \begin{pmatrix} U \\ D \\ D_- \end{pmatrix}$	$\frac{2}{3}$ $-\frac{1}{3}$ $-\frac{4}{3}$	$-\frac{2}{3}$	d_R through $\vec{W}^\mu$
$\frac{3}{2}$	$\mathcal{E}_M \begin{pmatrix} E^+ \\ E^0 \\ E^- \\ E^{--} \end{pmatrix}$	1 0 -1 -2	-1	$l_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ through $\vec{W}^\mu$	$\Psi_M \begin{pmatrix} U_+ \\ U \\ D \\ D_- \end{pmatrix}$	$\frac{5}{3}$ $\frac{2}{3}$ $-\frac{1}{3}$ $-\frac{4}{3}$	$\frac{1}{3}$	$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$ through $\vec{W}^\mu$

The hypercharge current J^Y_μ receives contributions only from $I_w = 0, \frac{1}{2}$ states as follows :

$$J^Y_\mu(I_w = 0) = -\left(\frac{f'_0}{m^*}\right)(\overline{E^-}\sigma_{\mu\nu}Q^\nu e_R + h.c.) + \left(\frac{2f'_{0u}}{3m^*}\right)(\overline{U}\sigma_{\mu\nu}Q^\nu u_R + h.c.)$$
$$-\left(\frac{f'_{0d}}{3m^*}\right)(\overline{D}\sigma_{\mu\nu}Q^\nu d_R + h.c.) \tag{2a}$$
$$J^Y_\mu(I_w = \frac{1}{2}) = -\left(\frac{f'}{2m^*}\right)(\overline{\mathcal{E}}\sigma_{\mu\nu}Q^\nu l_L + h.c.) + \left(\frac{f'_q}{6m^*}\right)(\overline{\Psi}\sigma_{\mu\nu}Q^\nu q_L + h.c.) \tag{2b}$$

where the notation follows that of Table I.

The isovector current $\vec{J}_\mu$ receives contributions from $I_w = \frac{1}{2}, 1$ and $\frac{3}{2}$:

$$\vec{J}_\mu(I_w = \frac{1}{2}) = \left(\frac{f}{m^*}\right)\left(\overline{\mathcal{E}}\sigma_{\mu\nu}Q^\nu\frac{\vec{\tau}}{2}l_L + h.c.\right) + \left(\frac{f_q}{m^*}\right)\left(\overline{\Psi}\sigma_{\mu\nu}Q^\nu\frac{\vec{\tau}}{2}q_L + h.c.\right) \tag{3a}$$

$$\vec{J}_\mu(I_w = 1) = \left(\frac{f_1}{m^*}\right)(\overline{\vec{\mathcal{E}}}\sigma_{\mu\nu}Q^\nu e_R + h.c.) + \left(\frac{f_{1u}}{m^*}\right)(\overline{\vec{U}}\sigma_{\mu\nu}Q^\nu u_R + h.c.) +$$
$$+\left(\frac{f_{1d}}{m^*}\right)\left(\overline{\vec{D}'}\sigma_{\mu\nu}Q^\nu d_R + h.c.\right) \tag{3b}$$

$$J_{\mu m}(I_w = \frac{3}{2}) = C(\frac{3}{2}, M \mid 1, m; \frac{1}{2}, m')\left[\left(\frac{f_3}{m^*}\right)(\overline{\mathcal{E}}_M\sigma_{\mu\nu}Q^\nu l_{Lm'} + h.c.) + \left(\frac{f_{3q}}{m^*}\right)(\overline{\Psi}_M\sigma_{\mu\nu}Q^\nu q_{Lm'} + h.c.)\right] \tag{3c}$$

The color current J^a_μ is composed of $I_w = 0, \frac{1}{2}$ contributions :

$$J^a_\mu(I_w = 0) = \left(\frac{f_{su}}{m^*}\right)\left(\overline{U}\sigma_{\mu\nu}Q^\nu\frac{\lambda^a}{2}u_R + h.c.\right) + \left(\frac{f_{sd}}{m^*}\right)\left(\overline{D}\sigma_{\mu\nu}Q^\nu\frac{\lambda^a}{2}d_R + h.c.\right) \tag{4a}$$

$$J^a_\mu(I_w = \frac{1}{2}) = \left(\frac{f_s}{m^*}\right)(\overline{\Psi}\sigma_{\mu\nu}Q^\nu q + h.c.) \tag{4b}$$

In the above equations, Q^μ denotes the momentum of the gauge field and m^* the mass of the excited fermion. In Eq.(3c), C's are Clebsch-Gordon coefficients . $\vec{\tau}$ and λ^a are the Pauli $SU(2)$ and Gell-Mann $SU(3)$ matrices respectively. W^μ_3 and B^μ are defined in the usual way :

$$B^\mu = cos\theta_w A^\mu - sin\theta_w Z^\mu \tag{5a}$$

$$W^\mu_3 = sin\theta_w A^\mu + cos\theta_w Z^\mu \tag{5b}$$

in terms of the physical fields A^μ for the photon and Z^μ for the Z_0, θ_w is the weak angle, with the gauge coupling constants g, g' and g_s given by :

$$\frac{g^2}{4\pi} = \frac{\alpha}{sin^2\theta_w} \quad ; \quad \frac{g'^2}{4\pi} = \frac{\alpha}{cos^2\theta_w} \tag{6a}$$

and

$$\frac{g_s^2}{4\pi} = \alpha_s(Q^2) \approx \frac{12\pi}{23\log\frac{Q^2}{\Lambda^2}} \quad (for\ five\ flavours). \tag{6b}$$

The various dimensionless coupling constants f and f' appearing in eqs.(2÷4) are expected to be of order unity. Their precise values can only be obtained theoretically on the basis of a given model for compositeness.

There are some immediate consequences regarding the particle structure implied by weak isospin and the corresponding interaction, which are independent of the strength of the magnetic moment couplings :

(i) Table I shows that for a given I_w, the total charge of a family

$$Q_{tot}^{I_w} = \sum_{l=lepton} Q_l^{I_w} + 3 \sum_{q=quarks} Q_q^{I_w}, \tag{8}$$

is automatically zero for $I_w=\frac{1}{2}$ and $\frac{3}{2}$. This is in keeping with the GIM mechanism[8] which requires $Q_{tot} = 0$ for each light quark-lepton family. A similar condition for $I_w=0$ forces upon us the entire set (E^-, U, D) and for $I_w=1$ the entire set $\left(\vec{\mathcal{E}}, \vec{U}, \vec{D}\right)$.

(ii) There are leptons (E^0 for $I_w=1$ and E^+ and E^{--} for $I_w=\frac{3}{2}$), which cannot decay radiatively but must undergo β-decay[3]. However, if they exist, the GIM mechanism forces upon us corresponding quarks with $I_w=1$ and $\frac{3}{2}$. On the other hand, all such excited quarks are coupled to light quarks not through the gluon but only through the EW gauge field $\vec{W}^\mu$. Their peculiarity lies in the fact that although they carry color and are presumably confined, they decay only electroweakly, either into $jet + \gamma$ or, via β-decay, into 3 $jets$ or $jet + l + \nu$.

(iii) Observation of even one $Z_0 \to \nu\bar{\nu}\gamma$ event would definitely rule out the bremmstrahlung mechanism for the observed $l^+l^-\gamma$ events[1,2] and favor strongly the existence of $I_w > 0$, $m^* < M_Z$ excited lepton(s)[*]. Once again, existence of such excited lepton(s) would imply that concomitant quark members[**] of the family exist as well. For the case $m^* < M_{W,Z}$, EW gauge fields can decay through excited exotic quarks with $I_w=1, \frac{3}{2}$, providing in some cases, startling final states,as we shall discuss towards the end.

(iv) quarks with $I_{weak} = 0$ have the pecularity of coupling to light quarks only through Z-boson and not through W. This is due to the fact that there are two excited singlets, U and D, coupling respectively to u_R and d_R only through the hypercharge field B^μ.

We now turn to a discussion of the possible decay channels, using the form of interaction introduced in eqs.(2÷4). Dominant decay modes and widths for $I_w=0$ and $I_w=\frac{1}{2}$ excited quarks and leptons are given in Table II. The corresponding cases for $I_w=1$ and $I_w=\frac{3}{2}$ are presented in Table III. In this table, $(f_1\bar{f}_2)^{\mp}$ represent a fermion-antifermion pair like for instance $(u\bar{d})$, and the phase space factor is defined as $\Phi_1(m^*, M_{IVB}) = \left(1-\frac{M_{IVB}^2}{m^{*2}}\right)^2\left(1+\frac{M_{IVB}^2}{2m^{*2}}\right)m^*$. $B_{f_1f_2}$ counts the number of open fermionic channels.Provided the masses of these states are below $Z_0, W^{\pm}$ masses, decay modes indicated in Table IV are expected to occur. These decays may be very interesting from the experimental point of view, both for $\bar{p}p$ and e^+e^- colliders. For the assignment $I_w=0$ and $I_w=\frac{1}{2}$ main decay channels are through quarks and gluons[4]. For excited leptons we refer to Table I of ref.3.

Next we discuss the production of excited quarks. To be definite, we shall discuss the production of $I_w=0, \frac{1}{2}, 1$ and $\frac{3}{2}$ quarks at $\bar{p}p$ colliders, through virtual exchanges of gluons and IVB's in the crossed channel and real or virtual IVB production in the direct channel.

The production of excited quarks, ϵ_k, through IVB exchanges are given, to lowest order, by the diagrams shown in fig.1. If we ignore interference terms between different exchanges, which should be a reasonable first approximation, the production cross-section may be written as :

$$\sigma(p\bar{p} \to \epsilon_k + X) = K \sum_{abc} \int dx \int dy\, q_a(x)\bar{q}_b(y) \int d\hat{t} \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{ab\to\epsilon_k c} \tag{7}$$

where $q(x)$ is the quark density in the proton and we have multiplied the cross-section by the usual K-factor ($\simeq 1.5 \div 2$). The partonic cross-sections are given by :

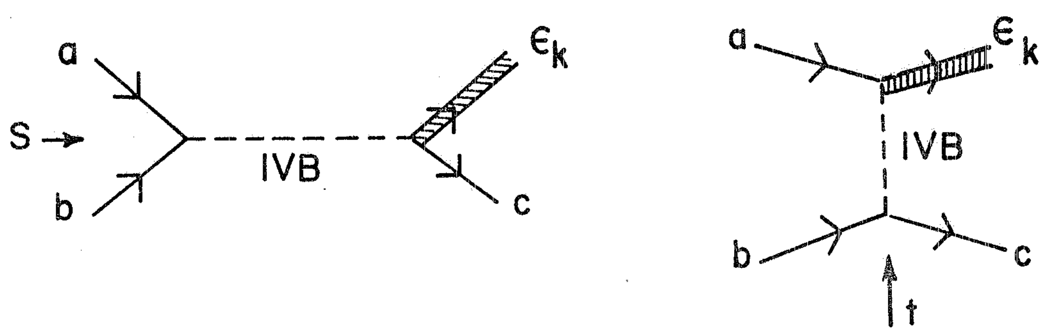

Fig. 1 : Diagrams contributing to the production of excited quarks through IVB's at hadron colliders.

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{ab\to e_{*}c} =$$

$$\frac{1}{4m^{*2}\hat{s}^2}\sum_i \frac{(G^k_{ci})^2}{4\pi}\frac{\hat{s}}{(M_i^2-\hat{s})^2+(M_i\Gamma)^2}\left\{\left[(V^i_{ab})^2+(A^i_{ab})^2\right]\bullet\left[m^{*2}\left(\hat{s}-m^{*2}\right)+2\hat{t}\hat{u}\right]\pm 2(V^i_{ab}A^i_{ab})m^{*2}(\hat{t}-\hat{u})\right\}$$

$$+\frac{1}{4m^{*2}\hat{s}^2}\sum_i \frac{(G^k_{ai})^2}{4\pi}\frac{\hat{t}}{(M_i^2-\hat{t})^2}\left\{\left[(V^i_{cb})^2+(A^i_{cb})^2\right]\bullet\left[m^{*2}\left(\hat{t}-m^{*2}\right)+2\hat{s}\hat{u}\right]\pm 2(V^i_{cb}A^i_{cb})m^{*2}(\hat{s}-\hat{u})\right\} \tag{9}$$

The $+sign$ should be used for $I_w = 0, 1$ and $-sign$ for $I_w=\frac{1}{2}, \frac{3}{2}$. V^i_{ab} and A^i_{ab} refer to the coupling of quarks a, b to a given vector boson i :

$$V^{W+}_{u\bar{d}} = -A^{W+}_{u\bar{d}} = \frac{e}{2\sqrt{2}sin\theta_w}$$

$$V^{Z_0}_{u\bar{u}} = \frac{e[3-8sin^2\theta_w]}{12sin\theta_w cos\theta_w} \quad ; \quad A^{Z_0}_{u\bar{u}} = -\frac{e}{4sin\theta_w cos\theta_w}$$

$$V^{Z_0}_{d\bar{d}} = \frac{e[-3+4sin^2\theta_w]}{12sin\theta_w cos\theta_w} \quad ; \quad A^{Z_0}_{d\bar{d}} = \frac{e}{4sin\theta_w cos\theta_w}$$

$$V^{\gamma}_{u\bar{u}} = \frac{2e}{3} \quad ; \quad V^{\gamma}_{d\bar{d}} = -\frac{e}{3} \quad A^{\gamma}_{u\bar{u}} = A^{\gamma}_{d\bar{d}} = 0 \tag{10}$$

The couplings G^k_{ci} can be inferred from eqs.(2) and (3). For $I_w = 0$

$$G^U_{\gamma u} = \frac{2e}{3}f'_{0u} \quad ; \quad G^U_{Z_0 u} = -\frac{2e}{3}tan\theta_w f'_{0u}$$

$$G^D_{\gamma d} = -(\frac{e}{3})f'_0 d \quad ; \quad G^D_{Z_0 d} = (\frac{e}{3}tan\theta_w)f'_{0d} \tag{11}$$

For $I_w=\frac{1}{2}$, G's are as follows :

$$G^U_{\gamma u} = e\left(\frac{1}{2}f_q + \frac{1}{6}f'_q\right) \quad ; \quad G^D_{\gamma d} = e\left(-\frac{1}{2}f_q + \frac{1}{6}f'_q\right)$$

$$G^U_{Z_0 u} = \frac{e}{sin\theta_w cos\theta_w}\left(\frac{1}{2}cos^2\theta_w f_q - \frac{1}{6}sin^2\theta_w f'_q\right) ; \; G^D_{Z_0 d} = \frac{-e}{sin\theta_w cos\theta_w}\left(\frac{1}{2}cos^2\theta_w f_q + \frac{1}{6}sin^2\theta_w f'_q\right)$$

$$G^U_{W+d} = \frac{e}{\sqrt{2}}\frac{f_q}{sin\theta_w} = G^D_{W-u}$$

For $I_w = 1$ one gets :

$$G^{U+}_{W+u} = G^{\overline{D}}_{W+\bar{u}} = \frac{e}{sin\theta_w}f_{1u}$$

TABLE II

I_w	Excited Leptons			
	Multiplet	Q	Main Decays	
			Mode	Width
0	E^-	-1	$E^- \to e^- + \gamma$	$\frac{1}{4}\alpha\|f'_0\|^2 m^*$
			$e^- + Z_0$	$\frac{1}{4}\alpha tan^2\theta_w \|f'_0\|^2 \Phi_1(m^*, M_Z)$
$\frac{1}{2}$	$\begin{pmatrix} E^0 \\ E^- \end{pmatrix}$	0	$E^0 \to \nu + \gamma$	$\frac{1}{4}\alpha\|\frac{f - f'}{2}\|^2 m^*$
			$\nu + Z_0$	$\frac{1}{4}\alpha\|\frac{f' sin^2\theta_w + f cos^2\theta_w}{2 sin\theta_w cos\theta_w}\|^2 \Phi_1(m^*, M_Z)$
			$e^- + W^+$	$\frac{1}{4}\alpha\|\frac{f}{\sqrt{2} sin\theta_w}\|^2 \Phi_1(m^*, M_W)$
		-1	$E^- \to e^- + \gamma$	$\frac{1}{4}\alpha\|\frac{f + f'}{2}\|^2 m^*$
			$e^- + Z_0$	$\frac{1}{4}\alpha\|\frac{f' sin^2\theta_w - f cos^2\theta_w}{2 sin\theta_w cos\theta_w}\|^2 \Phi_1(m^*, M_Z)$
			$\nu + W^-$	$\frac{1}{4}\alpha\|\frac{f}{\sqrt{2} sin\theta_w}\|^2 \Phi_1(m^*, M_W)$

I_w	Excited Quarks			
	Multiplet	Q	Main Decays	
			Mode	Fraction
0	U	$\frac{2}{3}$	$U \to u+g$	*dominant*
			$u+\gamma$	$\frac{1}{3}(\frac{\alpha}{\alpha_s})\vert\frac{f'_{0u}}{f_s}\vert^2 m^*$
			$u+Z_0$	$\frac{1}{3}(\frac{\alpha}{\alpha_s})tan^2\theta_w\vert\frac{f'_{0u}}{f_s}\vert^2\Phi_1(m^*,M_Z)$
	D	$-\frac{1}{3}$	$D \to d+g$	*dominant*
			$d+\gamma$	$\frac{1}{12}(\frac{\alpha}{\alpha_s})\vert\frac{f'_{0d}}{f_s}\vert^2 m^*$
			$d+Z_0$	$\frac{1}{12}(\frac{\alpha}{\alpha_s})tan^2\theta_w\vert\frac{f'_{0d}}{f_s}\vert^2\Phi_1(m^*,M_Z)$
$\frac{1}{2}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\frac{2}{3}$	$U \to u+g$	*dominant*
			$u+\gamma$	$\frac{3}{4}(\frac{\alpha}{\alpha_s})\vert\frac{f_q'+3f_q}{6f_s}\vert^2 m^*$
			$u+Z_0$	$\frac{3}{4}(\frac{\alpha}{\alpha_s})\vert\frac{3f_q cos^2\theta_w - f_q' sin^2\theta_w}{6f_s sin\theta_w cos\theta_w}\vert^2\Phi_1$
			$d+W^+$	$\frac{3}{4}(\frac{\alpha}{\alpha_s})\vert\frac{f_q}{\sqrt{2}f_s sin\theta_w}\vert^2\Phi_1(m^*,M_W)$
		$-\frac{1}{3}$	$D \to d+g$	*dominant*
			$d+\gamma$	$\frac{3}{4}(\frac{\alpha}{\alpha_s})\vert\frac{f_q'-3f_q}{6f_s}\vert^2 m^*$
			$d+Z_0$	$\frac{3}{4}(\frac{\alpha}{\alpha_s})\vert\frac{f_q' sin^2\theta_w + 3f_q cos^2\theta_w}{6f_s sin\theta_w cos\theta_w}\vert^2\Phi_1$
			$u+W^-$	$\frac{3}{4}(\frac{\alpha}{\alpha_s})\vert\frac{f_q}{\sqrt{2}f_s sin\theta_w}\vert^2\Phi_1(m^*,M_W)$

TABLE III

I_w	Multiplet	Q	Main Decays: Mode	Main Decays: Width
			Excited Leptons	
1	E^0	0	$E^0 \to e^- + (f_1 f_2)^+$	$\frac{1}{4}\alpha \mid \frac{f_1}{sin\theta_w}\mid^2 B_{f_1 f_2} m^*$
	E^-	-1	$E^- \to e^- + \gamma$	$\frac{1}{4}\alpha \mid f_1 \mid^2 m^*$
			$e^- + Z_0$	$\frac{1}{4}\alpha \mid \frac{f_1 cos\theta_w}{sin\theta_w}\mid^2 \Phi_1(m^*, M_Z)$
	E^{--}	-2	$E^{--} \to e^- + (f_1 f_2)^{--}$	$\frac{1}{4}\alpha \mid \frac{f_1}{sin\theta_w}\mid^2 B_{f_1 f_2} m^*$
$\frac{3}{2}$	E^+	$+1$	$E^+ \to \nu + (f_1 f_2)^+$	$\frac{1}{4}\alpha \mid \frac{f_3}{sin\theta_w}\mid^2 B_{f_1 f_2} m^*$
	E^0		$E^0 \to \nu + \gamma$	$\frac{1}{6}\alpha \mid f_3 \mid^2 m^*$
			$\nu + Z_0$	$\frac{1}{6}\alpha \mid \frac{f_3 cos\theta_w}{sin\theta_w}\mid^2 \Phi_1(m^*, M_Z)$
			$e^- + W^+$	$\frac{1}{12}\alpha \mid \frac{f_3}{sin\theta_w}\mid^2 \Phi_1(m^*, M_W)$
	E^-	-1	$E^- \to e^- + \gamma$	$\frac{1}{6}\alpha \mid f_3 \mid^2 m^*$
			$e^- + Z_0$	$\frac{1}{6}\alpha \mid \frac{f_3 cos\theta_w}{sin\theta_w}\mid^2 \Phi_1(m^*, M_Z)$
			$\nu + W^-$	$\frac{1}{12}\alpha \mid \frac{f_3}{sin\theta_w}\mid^2 \Phi_1(m^*, M_W)$
	E^{--}	-2	$E^{--} \to e^- + (f_1 f_2)^-$	$\frac{1}{4}\alpha \mid \frac{f_3}{sin\theta_w}\mid^2 B_{f_1 f_2} m^*$

I_w	Excited Quarks			
	Multiplet	Q	Main Decays: Mode	Main Decays: Width
1	U_+	$\frac{5}{3}$	$U_+ \to u + (f_1 f_2)^+$	$\frac{1}{4}\alpha\lvert\frac{f_{1u}}{sin\theta_w}\rvert^2 B_{f_1 f_2} m^*$
	U	$\frac{2}{3}$	$U \to u + \gamma$	$\frac{1}{4}\alpha\lvert f_{1u}\rvert^2 m^*$
			$u + Z_0$	$\frac{1}{4}\alpha\lvert\frac{f_{1u}cos\theta_w}{sin\theta_w}\rvert^2 \Phi_1(m^*, M_Z)$
	D	$-\frac{1}{3}$	$D \to u + (f_1 f_2)^-$	$\frac{1}{4}\alpha\lvert\frac{f_{1u}}{sin\theta_w}\rvert^2 B_{f_1 f_2} m^*$
	U	$\frac{2}{3}$	$U \to d + (f_1 f_2)^+$	$\frac{1}{4}\alpha\lvert\frac{f_{1d}}{sin\theta_w}\rvert^2 B_{f_1 f_2} m^*$
	D	$-\frac{1}{3}$	$D \to d + \gamma$	$\frac{1}{4}\alpha\lvert f_{1d}\rvert^2 m^*$
			$d + Z_0$	$\frac{1}{4}\alpha\lvert\frac{f_{1d}cos\theta_w}{sin\theta_w}\rvert^2 \Phi_1(m^*, M_Z)$
	D_-	$-\frac{4}{3}$	$D_- \to d + (f_1 f_2)^-$	$\frac{1}{4}\alpha\lvert\frac{f_{1d}}{sin\theta_w}\rvert^2 B_{f_1 f_2} m^*$
$\frac{3}{2}$	U_+	$\frac{5}{3}$	$U_+ \to u + (f_1 f_2)^+$	$\frac{1}{4}\alpha\lvert\frac{f_{3q}}{sin\theta_w}\rvert^2 B_{f_1 f_2} m^*$
	U	$\frac{2}{3}$	$U \to u + \gamma$	$\frac{1}{6}\alpha\lvert f_{3q}\rvert^2 m^*$
			$u + Z_0$	$\frac{1}{6}\alpha\lvert\frac{f_{3q}cos\theta_w}{sin\theta_w}\rvert^2 \Phi_1(m^*, M_Z)$
			$d + W^+$	$\frac{1}{12}\alpha\lvert\frac{f_{3q}}{sin\theta_w}\rvert^2 \Phi_1(m^*, M_W)$
	D	$-\frac{1}{3}$	$D \to d + \gamma$	$\frac{1}{6}\alpha\lvert f_{3q}\rvert^2 m^*$
			$d + Z_0$	$\frac{1}{6}\alpha\lvert\frac{f_{3q}cos\theta_w}{sin\theta_w}\rvert^2 \Phi_1(m^*, M_Z)$
			$u + W^-$	$\frac{1}{12}\alpha\lvert\frac{f_{3q}}{sin\theta_w}\rvert^2 \Phi_1(m^*, M_W)$
	D_-	$-\frac{4}{3}$	$D_- \to d + (f_1 f_2)^-$	$\frac{1}{4}\alpha\lvert\frac{f_{3q}}{sin\theta_w}\rvert^2 B_{f_1 f_2} m^*$

$$G^U_{W^+d} = G^D_{W^+\bar{d}} = \frac{e}{sin\theta_w} f_{1d}$$
$$G^U_{\gamma u} = e f_{1u} \quad ; \quad G^D_{\gamma d} = e f_{1d} \qquad (12)$$
$$G^U_{Z_0 u} = e\frac{cos\theta_w}{sin\theta_w} f_{1u} \quad ; \quad G^D_{Z_0 d} = e\frac{cos\theta_w}{sin\theta_w} f_{1d}$$

For $I_w = \frac{3}{2}$, one has :

$$G^{U+}_{W^+u} = \frac{e}{sin\theta_w} f_{3q} = G^D_{W^+\bar{d}} = \sqrt{3} G^U_{W^+d} = \sqrt{3} G^{\bar{D}}_{W^+u}$$
$$G^U_{\gamma u} = \sqrt{\frac{2}{3}} e f_{3q} = G^D_{\gamma d}$$
$$G^U_{Z_0 u} = \sqrt{\frac{2}{3}} e\frac{cos\theta_w}{sin\theta_w} f_{3q} = G^D_{Z_0 d} \qquad (13)$$

3. There are a number of very attractive experimental signatures which might reveal the presence of excited quarks at the $\bar{p}p$ collider. These signals are :

(i) a large production cross section for $jet + jet + \gamma$. If $m^* < M_Z$, Table IV gives :

$$R_Z = \frac{\Gamma(Z_0 \to jet + jet + \gamma)}{\Gamma(Z_0 \to e^+e^-)} = 3\frac{cos^4\theta_w}{sin^4\theta_w + (\frac{1}{2} - sin^2\theta_w)^2}(f_{1u}^2 + f_{1d}^2)\left(\frac{1 - m^{*2}}{M_Z^2}\right)^2\left(2 + \frac{M_Z^2}{m^{*2}}\right)$$

for I_w=1. For $m_F = 50GeV$, $f_{1u} \simeq f_{1d} \simeq \frac{1}{2}$ we find $R_Z \simeq 20$. This signal is present for all isospin values. The rate for I_w=$\frac{3}{2}$ is of the same order of magnitude as the one above. For I_w=0,1 the signal is very small, due to the presence of the dominant strong decay mode.

(ii) Charges $+\frac{5}{3}$ or $-\frac{4}{3}$ can undergo β-decay. For the case $m^* < M_W$ we have

$$W^+ \to 2jets + (f_1\bar{f}_2)^+ \qquad (4)$$

Such decays manifest themselves either through the appearance of more than 3 jets with an invariant total mass M_W or as an event with $2jets + l^+ +$ *missing energy* at the W-mass. The leptonic decay mode is a substantial fraction ($\frac{1}{5}$) of the signal with more than 3 jets. We can estimate how many events one may see, using again Table IV . For the case I_w=1 one gets :

$$R_W = \frac{\Gamma(W^+ \to jet_1 + jet_2 + l^+ + \nu)}{\Gamma(W^+ \to l^+ + \nu)} = 6B_{l^+\nu}(f_{1u}^2 + f_{1d}^2)\left(1 - \frac{m^{*2}}{M_W^2}\right)^2\left(2 + \frac{M_W^2}{m^{*2}}\right)$$

Table IV

Decay widths of Z_0 and W^+ through $I_w = 1, \frac{3}{2}$ excited quarks.

I_w	$\Gamma[Z_0 \to j_1 + j_2 + \gamma]$	$\Gamma[W^+ \to j_1 + j_2 + \gamma]$	$\Gamma[W^+ \to j_1 + j_2 + (f_1 \bar{f}_2)^+]$
1	$\frac{\alpha}{2}\left(\frac{cos^2\theta_w}{sin^2\theta_w}\right)[f_{1u}^2 + f_{1d}^2]\Phi(M_Z, m^*)$	0	$\frac{\alpha}{2}\frac{f_{1u}^2 + f_{1d}^2}{sin^2\theta_w}\Phi(M_W, m^*)B_{f_1\bar{f}_2}$
$\frac{3}{2}$	$\frac{2\alpha}{3}\left(\frac{cos^2\theta_w}{sin^2\theta_w}\right)f_{3q}^2\Phi(M_Z, m^*)$	$\frac{\alpha}{6}\left(\frac{f_{3q}^2}{sin^2\theta_w}\right)\Phi(M_W, m^*)$	$\frac{\alpha}{2}\frac{f_{3q}^2}{sin^2\theta_w}\Phi(M_W, m^*)B_{f_1\bar{f}_2}$

<u>Note</u> :j_i refers to u or d jets, the phase space factor is given as

$$\Phi(M_{IVB}, m^*) = \left(2 + \frac{M_{IVB}^2}{m^{*2}}\right)\left(1 - \frac{m^{*2}}{M_{IVB}^2}\right)^2 M_{IVB}$$

The branching ratios $B_{f_1\bar{f}_2}$ count the relative weight from open fermionic channels.

Again, for a mass $m^* \simeq 50GeV$, $f_{1u} \simeq f_{1d} \simeq \frac{1}{2}$ and $B_{l^+\nu} = \frac{1}{5}$, we now find $R_W \simeq 1.3$.

(iii) The above argument can be repeated for the second family ($u \to c$ and $d \to s$). We then have the possibility of two same sign leptons or even 3 leptons :

$$\begin{array}{l} W^+ \to \bar{c} + C_+ \\ \qquad\qquad \hookrightarrow c + \mu^+ + \nu_\mu \\ \qquad\qquad\qquad \hookrightarrow s + \mu^+ + \nu_\mu \\ \qquad\quad \hookrightarrow \bar{s} + (f_1 \bar{f}_2)^- \end{array} \tag{15}$$

For this case the relative probability is 4% to get a characteristic $\mu^+\mu^+$ signal and 0.8% to get a $\mu^+\mu^+\mu^-$ signal with respect to the total $\bar{c}c^*_+$ decay mode.Electrons are produced with similar rates.

For a possible third excited lepton family the multiplet with $I_{weak} = \frac{3}{2}$ can couple to the light doublet $\binom{\nu_\tau}{\tau}$ to produce

$$\begin{array}{l} W^+ \to \overline{T^{--}} \tau_- \\ \qquad\quad \hookrightarrow \tau_+ + (f'_1 \bar{f}'_2)^+ \\ \qquad\qquad \hookrightarrow \bar{\nu_\tau} + (f_1 \bar{f}_2)^+ \end{array} \tag{16}$$

Once again, l^+l^+ and $l^+l^+l^-$ signals are produced with relative intensities equal to those for eq.(15) decays.

(iv) The possibility exists that some of these new particles are heavier than the IVB so that decays of excited quarks into W and Z can be considered. The most intriguing possibility is that of I_w=0 excited quarks, for which decay into the light quarks is allowed only through the Z_0. Indeed, if these quarks are heavier than the IVB, then Z <u>but not W</u> could be produced through gluon exchange in the crossed channel. The above would constitute a mechanism which distinguishes between Z_0 and W production and which is characterized by the presence of more jet activity in the case of Z_0. One could then determine the strength of the coupling $f_{0u,d}$ of the singlet stark to the the light quarks, by a comparison of jets associated with W and Z_0.

For this channel, quark-gluon fusion might produce the signal

$$single\ jet + missing\ energy$$

while gluon exchange could produce

$$2\,(opposite\ side)\,jets + missing\,energy$$

with no contribution to the signal

$$jet(s) + electron + missing\,energy$$

(v) For the Cern collider, the search for these new states can be reasonably limited to $m^* \leq 150\,GeV$, since production of masses beyond this range would be considerably suppressed for lack of sufficient parton luminosity at large x. We remark that while some of these particles couple through gluons, there are distinctive possibilities for quantum states which can only be reached through IVB and photons, like for instance all states with $I_w \geq 1$.

(vi) Finally we point out that if $I_w \geq 1$ quark exist, they would produce the following exotic hadronic states :

<u>exotic mesons</u> : charge ± 2 $\quad (U_+\bar{d})\,(D_-\bar{u})$

<u>exotic baryons</u> : charge $+3$ $\quad (U_+uu)$

The masses of such hadrons would be $\approx m^*$. Needless to say that if m^* is not too large, the search for the top quark and supersymmetric particles would be complicated since these hadrons, exotic or otherwise would have rather similar decay signals.

In conclusion,considerations from weak isospin alone lead to some very specific predictions regarding the pattern of excited quarks and leptons which should be experimentally investigated by the present and future generations of hadron and e^+e^- colliders.

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Footnotes

[*] A 'light' excited muon with mass $\simeq 60 GeV$[3] does not conflict with the measured $(g-2)$ anomaly for the muon, provided of course the coupling is of the $(V-A)$ type - a condition naturally satisfied here.

[**] Induced parity violations in strong interactions through excited quarks are comfortably small for $m^* \geq 50 GeV$ to cause any conflict with the available data.