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G. Pancheri: EXCITED FERMIONS

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EXCITED FERMIONS

G. Pancheri

INFN, Laboratori Nazionali di Frascati,Frascati,POB 13 - 00044 Frascati (Italy)

Abstract

Theoretical and experimental implications of the existence of excited states of ordinary leptons and quarks are examined. The contribution of excited electrons and of their neutral partners to the decays $Z_0 \to e^+e^-\gamma$ and $Z_0 \to \nu\bar{\nu}\gamma$ are discussed. Signatures of excited quark states are compared with reported experimental observations. Through weak isospin invariance,it is also found that there may exist excited quarks with weak isospin $I_w \geq 1$ which have exotic charge assignments and decay only electroweakly into ordinary quarks and leptons. These exotic quarks will give rise to charge $+3$ baryons and charge ± 2 mesons.

1. EXPERIMENTAL MOTIVATION

In 1983 UA1 and UA2 Collaboration reported the observation of the process

$$Z_0 \to e^+e^-\gamma \quad (1\ event\ each)$$

and

$$Z_0 \to \mu^+\mu^-\gamma \quad (1\ event)$$

as well as $Z_0 \rightarrow e^+e^-$ and $Z_0 \rightarrow \mu^+\mu^-$ for a total of 13 dilepton events[1,2]. The energy and emission angle of the observed photons, which we reproduce in Table I from ref.[3] , do not favour a conventional explanation in terms of hard bremsstrahlung [4]. Furthermore at this conference, there has been reported the observation of other unusual events :

TABLE I - Properties of the $l^+l^-\gamma$ events.

	$e^+e^-\gamma$ (UA1)	$e^+e^-\gamma$ (UA2)	$\mu^+\mu^-\gamma$ (UA1)
E_γ (GeV)	38.8 ± 1.5	24.4 ± 1.0	28.3 ± 3
E_{ℓ^+} (GeV)	61.0 ± 1.2	69.9 ± 1.8	$50.6^{+5.8}_{-4.7}$
E_{ℓ^-} (GeV)	9 ± 1	11.5 ± 0.7	$42.2^{+44.0}_{-14.3}$
$\Delta\alpha^{a)}(\ell^+\gamma)$	132.0 ± 4.0	129.9	7.9
$\Delta\alpha^{a)}(\ell^-\gamma)$	14.4 ± 4.0	31.8	99.0
$m(\ell^+\ell^-)$ $\left(\frac{GeV}{c^2}\right)$	42.7 ± 2.4	50.4 ± 1.7	$70.9^{+37.2}_{-12.4}$
$m(\ell^+\ell^-\gamma)$ $\left(\frac{GeV}{c^2}\right)$	98.7 ± 5.0	90.6 ± 1.9	$88.4^{+46.1}_{-15.2}$
$m(\ell^+\gamma)$ $\left(\frac{GeV}{c^2}\right)$	88.8 ± 2.5	74.7 ± 1.8	5.0 ± 0.4
$m(\ell^-\gamma)$ $\left(\frac{GeV}{c^2}\right)$	4.6 ± 1.0	9.1 ± 0.3	$52.5^{+27.5}_{-9.3}$

a) $\Delta\alpha$ is the angular difference in space.

$$p\bar{p} \rightarrow missing\ energy + \text{'}photon\text{'} + X \quad (UA1)$$

and

$$p\bar{p} \rightarrow missing\ energy + \ single\ jet + X \quad (UA1)$$

with large value of transverse missing energy and large p_t values for the photon and the jet [5] and

$$p\bar{p} \rightarrow electron\ +\ missing\ energy\ +\ hard\ jet(s) + X \quad (UA2)$$

with a large total invariant mass [6]. Tables II, III and IV reproduce the characteristics of these events as reported by the experimental groups.

Many suggestions have been advanced to explain the anomalous Z_0 events [7–12]. In this talk I shall discuss in detail a model of excited quarks and leptons which bears the signatures of the reported events, although the event topology shows other anomalies[7] and the production rates are not fully consistent between the different processes.

2. THE EXCITED FERMION MODEL

The excited fermion model is based on the idea that if quarks and leptons are composite objects[13], there may exist excited states which are coupled to ordinary fermions through the usual electroweak fields as well as through the gluon field and in a such a way so as to conserve weak isospin. The excited fermion hypothesis can be phenomenologically understood as an extension of the known three families of light leptons and quarks through the use of weak isospin. In the standard $SU(2) \times U(1)$ model, the known particles can be classified as belonging to weak isospin multiplets: right (left) handed fermions belong to isospin singlets (doublets) and the gauge bosons belong to triplets, $\vec{W}^\mu$, or singlets, B^μ. To the electroweak fields, one can add the color field $G^{\mu a}$ which behaves like a singlet under weak isospin transformations. One may then consider the existence of fermionic states which can be excited using light fermions (I_w=0,$\frac{1}{2}$), Intermediate Vector Bosons (I_w=0,1) and gluons (I_w=0). To lowest order in α only I_w=0,$\frac{1}{2}, 1, \frac{3}{2}$ need be considered. The resulting spectroscopy is very similar in spirit to the one which was done in the early days of particle physics when the nucleon isodoublet and the pion isotriplet had been used to obtain the spectrum of many of the non-strange baryonic resonances. Since all the gauge fields carry no hypercharge Y, only couplings between excited and light multiplets with the same value of Y are allowed. As it is well known, the effective coupling has to be of the magnetic moment type transition for current conservation. This leads to the following effective lagrangian :

$$\mathcal{L}_{eff} = g' B^\mu J^Y_\mu + g\vec{W}^\mu \cdot \vec{J}_\mu + g_s G^{\mu a} J^a_\mu \tag{1}$$

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

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

TABLE II - Properties of the isolated "photon" events (UA1).

Run, event	E_{tot} (GeV)	$\|E_T\|$ (GeV)	ΔE_M (GeV)	$E_T(\gamma)$ (GeV)	$m_T(\gamma,\Delta E_M)$ (GeV/c²)
H 8167 90	298	91	40 ± 4	54	93 ± 5
G 7856 1020	390	104	40 ± 6	44	84 ± 6

TABLE III - Properties of single jet events (UA1).

Run, event	General event properties				Jet properties					
	E_{TOT} (GeV)	$\|E_T\|$ (GeV)	ΔE_M (GeV)	$m_T(\text{Jet},\Delta E_M)$ (GeV/c²)	E_T (GeV)	E_T^{elm} a) (GeV)	ϕ b) (deg)	η c)	$p_T \pm \Delta p_T$ d) (GeV/c)	m_{CH} (GeV/c²)
A 7325 808	300	48 94*	24 ± 4.8 (66 ± 8)*	130 ± 16	25 71*	12.4	152	-1.13	$+46^{+12}_{-8}$	single track
B 7157 506	294	90	59 ± 7	106 ± 12	48	23.3	-142	-0.39	$-7.3^{+1.2}_{-0.9}$ $+10.1^{+2.5}_{-1.7}$ $+3.7^{+0.2}_{-0.18}$	0.79 ± 0.12
C 7513 1212	489	129	46 ± 8	97 ± 17	52	44.4	176	-0.03	$-2.9^{+0.35}_{-0.29}$	e)
D 7304 1270	279	75	42 ± 6	85 ± 12	43	42.1	-34	-0.04	$-13.0^{+5.5}_{-3.0}$ $K^0\begin{cases} -1.83^{+0.07}_{-0.065} \\ +0.92^{+0.012}_{-0.12} \end{cases}$ $+0.89^{+0.07}_{-0.007}$	3.14 ± 0.38
E 8072 615	398	92	41 ± 7	87 ± 14	46	29.9	173	0.62	$+0.86^{+0.051}_{-0.045}$ $-0.61^{+0.04}_{-0.04}$	unreconstructed tracks
F 8032 1158	405	93	34 ± 7	73 ± 14	39	36.2	41	-0.31	$-4.8^{+0.32}_{-0.28}$ $-7.6^{+0.8}_{-0.66}$	0.517 ± 0.06

a) Electromagnetic part of the jet transverse energy.
b) Azymuthal angle ϕ.
c) Rapidity $\eta > 0$ in direction of outgoing $\bar{p}$.
d) Charged tracks associated to the jet with $p_t > 0.5$ GeV/c. Errors are statistical only.
e) This event could have other unreconstructed tracks in the horizontal plane.
*) Including the muon momentum in the calculation.

TABLE IV - Properties of the electron + missing energy + jet(s) events. (UA2)

Events		A	B	C	Units
Electron	$p_T(e)$	18.3 ± 0.8	22.0 ± 0.9	34.4 ± 3.2	GeV/c
	$\eta(e)$ a)	0.02	-0.23	0.24	
Jets b)	$p_T(j_1)$	27 ± 3	67 ± 7	38 ± 5	GeV/c
	$\eta(j_1)$ a)	- 0.59	- 0.26	0.07	
	$\Delta\phi(j_1)$ c)	50	310	311	degrees
	$p_T(j_2)$	6 ± 1		21 ± 3	GeV/c
	$\eta(j_2)$ a)	0.50		0.12	
	$\Delta\phi(j_2)$ c)	93		183	degrees
	$p_T(j_3)$	5 ± 1		7 ± 1	GeV/c
	$\eta(j_3)$ a)	- 1.09		-1.38	
	$\Delta\phi(j_3)$ c)	70		316	degrees
	$E_T(J)$	39 ± 4	67 ± 7	66 ± 6	GeV
	$m(J)$			63 ± 5	GeV/c^2
	$p_T(\nu)$	51 ± 4	86 ± 6	57 ± 5	GeV/c
	$\Delta\phi(\nu)$ c)	220	141	141	degrees
	$m_T(e\nu)$	56 ± 2	81 ± 3	82 ± 4	GeV/c^2
1	$m(WJ)$	179 ± 7	176 ± 9	162 ± 8	GeV/c^2
	$x_F(WJ)$	0.45 ± 0.04	-0.01 ± 0.06	-0.04 ± 0.05	
2	$m(WJ)$	141	166	164	GeV/c2
	$x_F(WJ)$	-0.55	- 0.31	0.13	

a) The pseudo-rapidity η is positive in the proton direction.

b) As mentionad in ref. (6), jet energies are expected to be smaller than the parent parton energies. This has not been corrected for and affects all parameters depending upon jet energies.

c) $\Delta\phi$ is the azymuth difference with respect to the electron.

$$J^Y_\mu(I_w = \frac{1}{2}) = -\left(\frac{f'}{2\mu}\right)(\bar{\mathcal{E}}\sigma_{\mu\nu}Q^\nu l_L + h.c.) + \left(\frac{f'_q}{6\mu}\right)(\bar{\Psi}\sigma_{\mu\nu}Q^\nu q_L + h.c.) \tag{2b}$$

where the notation follows that of Table V and VII, where the multiplet structure of the excited fermions is described in detail and μ represents the mass of the excited fermion.

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

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

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

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

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

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

$$J^a_\mu(I_w = \frac{1}{2}) = \left(\frac{f_s}{\mu}\right)\left(\overline{\Psi}\sigma_{\mu\nu}Q^\nu \frac{\lambda^a}{2} q_L + h.c.\right) \qquad (4b)$$

In the above equations, Q^μ denotes the momentum of the gauge field and μ 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 :

$$B^\mu = \cos\theta_w A^\mu - \sin\theta_w Z^\mu \qquad (5a)$$

$$W^\mu_3 = \sin\theta_w A^\mu + \cos\theta_w Z^\mu \qquad (5b)$$

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 :

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

and

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

The constants appearing in the above equations, f, f' and f_s will have to be determined by the experimental observations because of our lack of understanding of the underlying dynamics. As for the mass of such excited states, while there are no estimates from first principles, earlier guesses had placed it in the TeV range, i.e. in the range of a possible composite scale Λ[14]. Indeed there are indications, from Bhabha scattering for instance, that the composite scale cannot be less than $750GeV$[15]. Present interest in the interpretation of the collider events, would instead favour a mass in the $60 \div 150GeV$ range, i.e. of the same order of magnitude of the Intermediate Vector Boson

(IVB) mass.

It is important to notice that the experimental limits on the mass of an excited lepton are consistent with

$$\mu \geq 60GeV$$

and a coupling of order unity. In ref.[7], it has been pointed out that coupling of excited leptons to the light ones may generate flavour changing neutral current processes which are of order $(\frac{m}{\mu})^4$ with respect to ordinary weak interactions. Thus the effect is very small if the mass m of the ordinary leptons does not exceed that of the τ and that of the excited ones is not less than, say, $\simeq 50GeV$.

Limits on both the mass and the coupling are placed by the measurement (at both Petra and PeP) of the cross-section for the process

$$e^+e^- \rightarrow \gamma\gamma$$

Present data [16] are consistent with the constraint

$$2\sqrt{2}\mu^2 \geq (60GeV)^2|f+f'|$$

Finally, more stringent limits on these same quantities can be derived from the measured value of $(g-2)$ for the muon [17]. In this case while a pure vector or a pure axial vector type coupling would give a contribution linear in $\frac{m}{\mu}$, hence large for any reasonable μ mass, the requirement that the coupling be of the $V-A$ type leads to a correction like [7,18]

$$\delta(g-2) = \frac{9\alpha}{16\pi}(f+f')^2(\frac{m_\mu}{\mu})^2$$

For $\mu \geq 60GeV$ this implies

$$|f+f'| < 1.5$$

All of the above tells us that, while plausibility arguments would place the excited lepton mass in the TeV range, there are no experimental counterindications for a 'low' mass, like $60 \div 150GeV$ and that the coupling may be of the same order of magnitude than that of the usual weak interactions.

Thus both experimental and theoretical constraints seem to allow for excited fermions. Naturally, one may then also consider the idea of new massive sequential states to not just quarks and leptons but also to IVB's. This has been the object of many investigations [19−21]. In particular, and to explain the anomalous Z-decays, there has been advanced the hypothesis of a direct coupling between Z_0, γ and a scalar (or pseudoscalar) resonance which decays into e^+e^-. From the experimental data, shown in Table I, one would expect such a state to be in the $40 \div 50GeV$ range. Recent investigations at Petra [22] of the possible decay channels of such a state seem to exclude the presence of a resonance in the processes

$$e^+e^- \to hadrons,\ \mu^+\mu^-, e^+e^-, \gamma\gamma$$

at least up to energies of $45.22 GeV$. At the same time it has been shown[23,24] that the contribution of such a state to the $(g-2)$ of the muon would be quite large and could be cancelled only by the contribution from an almost mass-degenerate pseudoscalar (or scalar) partner . This would imply an hitherto unknown symmetry of the lagrangian.

3. EXCITED LEPTONS

The multiplet structure resulting from the excited fermion model was studied for the leptons in ref.[7] and is shown in Table V. This table indicates that if the excited leptons are lighter than the IVB's, the following decay modes can be observed :

$$Z_0 \to e^+e^-\gamma \qquad I_w = 0, \frac{1}{2}, 1, \frac{3}{2}$$

$$Z_0 \to \nu\bar{\nu}\gamma \qquad I_w = \frac{1}{2}, \frac{3}{2}$$

$$W \to e\nu\gamma \qquad I_w = \frac{1}{2}, \frac{3}{2}$$

$$W \to e^+e^-(f_1\bar{f}_2) \qquad I_w = 1, \frac{3}{2}$$

$$W \to \nu\bar{\nu}(f_1\bar{f}_2) \qquad I_w = \frac{3}{2}$$

where $(f_1\bar{f}_2)$ represent a fermion-antifermion pair belonging to the same isospin multiplet. For the case $I_w = \frac{1}{2}$, the calculation of the expected IVB decay rates into the above radiative channels produces the rates shown in Table VI, where

$$r = |f\cos^2\theta_w - f'\sin^2\theta_w|^2\left(2 + (\frac{M_z}{\mu})^2\right)\left(1 - (\frac{\mu}{M_z})^2\right)^2 \frac{1}{1 - 4\sin^2\theta_w + 8\sin^4\theta_w}$$

and

$$\rho = \frac{M_w^2 + 2\mu^2}{M_z^2 + 2\mu^2}\left(\frac{M_w^2 - \mu^2}{M_z^2 - \mu^2}\right)^2\left(\frac{M_z}{M_w}\right)^4(1 - 4\sin^2\theta_w + 8\sin^4\theta_w)$$

With the values

$$|f\cos^2\theta_w - f'\sin^2\theta_w| \simeq \frac{1}{2}$$

and

$$\mu = 75\, GeV$$

TABLE V - Quantum numbers (charge Q, hypercharge Y) of excited leptons (belonging to the first family) with $I_W \leq 3/2$ and their coupling to light leptons with same Y.

I_W^*	Multiplet	Q	Y	Coupled to	I_W
0	E^-	-1	-2	e_R through B^μ	0
1/2	$\mathcal{E} \equiv \begin{pmatrix} E^0 \\ E^- \end{pmatrix}$	0 -1	-1	$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$ through $\vec{W}^\mu$ and B^μ	1/2
1	$\vec{\mathcal{E}} \equiv \begin{pmatrix} E^0 \\ E^- \\ E^{--} \end{pmatrix}$	0 -1 -2	-2	e_R through $\vec{W}^\mu$	0
3/2	$\mathcal{E} \equiv \begin{pmatrix} E^+ \\ E^0 \\ E^- \\ E^{--} \end{pmatrix}$	+1 0 -1 -2	-1	$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$ through $\vec{W}^\mu$	1/2

TABLE VI - IVB's radiative decay rates, $I_W = 1/2$.

$\dfrac{\Gamma(Z_0 \to e^+e^-\gamma)}{\Gamma(Z_0 \to e^+e^-)}$	$\dfrac{\Gamma(Z_0 \to \nu_e \bar{\nu}_e \gamma)}{\Gamma(Z_0 \to e^+e^-)}$	$\dfrac{\Gamma(W^+ \to e^+\nu_e\gamma)}{\Gamma(W^+ \to e^+\nu_e)}$
γ	$\gamma \left\| \dfrac{f\cos^2\theta_W + f'\sin^2\theta_W}{f\cos^2\theta_W - f'\sin^2\theta_W} \right\|^2$	$\rho\gamma \left\| \dfrac{f}{f\cos^2\theta_W - f'\sin^2\theta_W} \right\|^2$

one obtains good agreement with the experimental observations, i.e. a ratio

$$r = 0.2$$

for $Z_0 \rightarrow e^+e^-\gamma$ relative to $Z_0 \rightarrow e^+e^-$ and no $W \rightarrow e\nu\gamma$ in excess of the expected QED background[25]. These values of the parameter bear a very definite prediction : the existence of the decay mode

$$Z_0 \rightarrow \nu\bar{\nu}\gamma.$$

The number of expected events depends upon :

(a) the weak isospin assignment, $I_w = \frac{1}{2}$ and/or $I_w = \frac{3}{2}$,

(b) for each I_w, the number of excited families contributing to the decay,

(c) the relative sign, and magnitude, of f and f'.

Nothing can be said about the isospin, although it is plausible that it be $I = \frac{1}{2}$. On the other hand, the observation of the $\mu^+\mu^-\gamma$ mode implies the existence of at least two excited families. For two families and $I_w = \frac{1}{2}$,one has

$$r_0^\nu = \frac{\Gamma(Z_0 \rightarrow \nu\bar{\nu}\gamma)}{\Gamma(Z_0 \rightarrow e^+e^-)} = 2r\left|\frac{f\cos^2\theta_w + f'\sin^2\theta_w}{f\cos^2\theta_w - f'\sin^2\theta_w}\right|^2$$

Lacking insight into the dynamics of the model, one cannot predict this ratio and must wait for more experimental or theoretical information. During the last year, the UA1 Collaboration has searched for this type of events and has reported,at this conference, the observation of two events, with the characteristics indicated in Table II. Both events are compatible with Z_0-decay, although one cannot exclude the possibility that the photon of event G is an electron, which has passed through the region where the central detector is not sensitive.

Another interesting prediction of the excited lepton hypothesis is the exixtence of $I_w > \frac{1}{2}$ multiplets with exotic charge states, like a positively charged electron E^+ and a doubly charged E^{--}. These leptons can only have β-decays and are coupled to light leptons only through W^+ and W^-. If the mass is in the $70 \div 80\,GeV$ range, the decay rate is however very small. With present statistics on W-decay modes, one expects

$$W \rightarrow e^+e^-(f_1\bar{f}_2)^+ \qquad I_w = 1, \frac{3}{2}$$

with $\simeq$ 1 event in the e^+e^- *jet jet* channel and

$$W^+ \rightarrow \nu\bar{\nu}(f_1\bar{f}_2)^+ \quad I_w = \frac{3}{2}$$

with $1 \div 2$ events in the *missing energy* + $2jets$ channel and $0.2 \div 0.3$ events in the *electron* + *missing energy* channel.The signature of the latter events differ from the usual $W \rightarrow e\nu$ decay because the electron should be substantially less energetic than the 'neutrino'.

4. THE QUARK SECTOR

The excited lepton hypothesis can easily be extended to the quark sector. One finds that excited quarks can be divided into two groups, those which predominantly decay strongly[26] and for which the decay width is

$$\Gamma \approx \alpha_s \mu \qquad I_w = 0, \frac{1}{2}$$

and the others which have only electroweak decay modes[27], i.e.

$$\Gamma \approx \alpha \mu \qquad I_w = 1, \frac{3}{2}$$

Table VII shows the quantum numbers of excited quarks belonging to the first family and their coupling to light quarks with same hypercharge.

4.1 The case $I_w = 0, \frac{1}{2}$.

The case $I_w = \frac{1}{2}$ has been considered in detail in ref. [26], where quark-gluon fusion was found to be an important production mechanism for $I_w = \frac{1}{2}$ excited quarks. Once produced these quarks (starks) can then decay as shown in Figs. 1a, b and c, the latter mode being allowed only if the stark is heavier than the IVB. De Rujula et al. have calculated the production cross-section for these processes relative to the QCD background[28] . For process (a) and before integrating over the parton densities, the cross-section can be written as

$$\frac{d\sigma}{dM^2_{jj}} = \frac{\pi \alpha_s}{3} {f_s}^2 \frac{\mu \Gamma}{(M^2_{jj} - \mu^2)^2 + \mu^2 \Gamma^2} \delta(M^2_{jj} - \hat{s})$$

with

$$\Gamma = \frac{\alpha_s}{3} {f_s}^2 \mu$$

In this model the constant f,f' and f_s are all of the same order of magnitude. Imposing some kinematical cuts and for a stark mass $\mu = 140 GeV$ De Rujula et al. expect an excess of $\simeq 20$ events in the jet-jet cross-section with $\alpha_s = 0.1$. These estimates are strongly dependent on the values of the coupling constants (f=f'=$f_s = \frac{1}{2}$ in this case) and have un uncertainty of at least a factor $2 \div 3$. This signal is consistent with the observation of an excess of $\simeq 50 \pm 16$ events in the jet-jet cross-section around 140 GeV, reported at this conference by the UA2 Collaboration [29] . If

TABLE VII - Quantum numbers (charge Q, hypercharge Y) of excited quarks (belonging to the first family) with $I_W \leq 3/2$ and their coupling to light quarks with same Y.

I_W^*	multiplet	Q	Y	Coupled to	I_W
0	U	2/3	4/3	u_R through B^μ, $G^{\mu a}$	0
	D	-1/3	-2/3	d_R through B^μ, $G^{\mu a}$	
1/2	$\Psi \equiv \begin{pmatrix} U \\ D \end{pmatrix}$	2/3 -1/3	1/3	$\begin{pmatrix} u \\ d \end{pmatrix}_L$ through $\vec{W}^\mu$, B^μ, $G^{\mu a}$	1/2
1	$\vec{U} \equiv \begin{pmatrix} U_+ \\ U \\ D \end{pmatrix}$	5/3 2/3 -1/3	4/3	u_R through $\vec{W}^\mu$	0
	$\vec{D} \equiv \begin{pmatrix} U \\ D \\ D_- \end{pmatrix}$	2/3 -1/3 -4/3	-2/3	d_R through $\vec{W}^\mu$	
3/2	$\Psi \equiv \begin{pmatrix} U_+ \\ U \\ D \\ D_- \end{pmatrix}$	5/3 2/3 -1/3 -4/3	1/3	$\begin{pmatrix} u \\ d \end{pmatrix}_L$ through $\vec{W}^\mu$	1/2

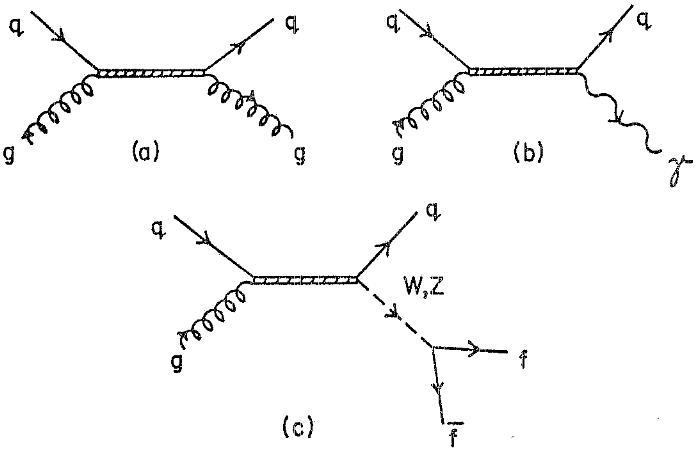


FIG. 1

this excess in indeed due to production of a stark of mass $\simeq 140\,GeV$, one must then look for the various final states which are opened by the presence of the decay channel

$$q^* \to IVB + q$$

and in particular :

(a) an enhancement in the 3 jet cross-section,

(b) events of the type lepton + missing energy + hard jet,

(c) events of the type missing energy or e^+e^- + hard jet.

Notice that for $I_w = 0$, some of the above channels are precluded, in particular there is no stark decay into W and light quarks. The expected number of events for $I_w = \frac{1}{2}$can be calculated making use of the branching ratios

$$\frac{\Gamma(q^* \to IVB + q)}{\Gamma(q^* \to all)} = \frac{3\alpha}{4\alpha_s}\left|\frac{f_v}{f_s}\right|^2\left(1 - \frac{M_{IVB}{}^2}{\mu^2}\right)^2\left(1 + \frac{M_{IVB}{}^2}{2\mu^2}\right)$$

with

$$f_\gamma = \frac{\tau_3}{2}f + \frac{1}{6}f'$$
$$f_z = \frac{\cos\theta_w}{\sin\theta_w}\frac{\tau_3}{2}f - \frac{1}{6}\frac{\sin\theta_w}{\cos\theta_w}f'$$
$$f_w = \frac{1}{\sqrt{2}\sin\theta_w}f$$

and

$$\frac{\Gamma(Z_0 \to \nu\bar{\nu})}{\Gamma(Z_0 \to all)} = 0.18 \tag{7}$$
$$\frac{\Gamma(W \to e\nu)}{\Gamma(W \to all)} = 0.1$$

Eq.(7) implies that if the six 'monojet' events reported by the UA1 Collaboration[5] are interpreted as due to the process

$$\begin{array}{l} p\bar{p} \to q^* + X \\ \qquad\quad \hookrightarrow Z_0 + q \\ \qquad\qquad \hookrightarrow \nu\bar{\nu} \end{array}$$

one should expect one

$$p\bar{p} \to e^+e^- + (hard)\ jet + X$$

event. Table VIII gives some estimate of the expected number of events for both $I_w = 0$ and $I_w = \frac{1}{2}$ case, with $\mu = 140\,GeV$.

TABLE VIII

I_w	N_{jj}	$N_{e\nu j}$	$N_{\nu\bar{\nu}j}$	$N_{j\gamma}$	N_{jjj}
0	20	0	5×10^{-3}	0.36	2×10^{-2}
	50	0	1.3×10^{-3}	0.9	5×10^{-2}
$1/2$	20	0.12	5×10^{-2}	0.36	0.94
	50	0.3	0.13	0.9	2.34

$\alpha_s = 0.1$, $M_W = 83$ GeV, $M_Z = 95$ GeV.

4.2 Excited Quarks with $I_w = 1, \frac{3}{2}$.

Excited quarks with higher isospin assignments have, as already mentioned, quite different signatures. Their main characteristics is that, to lowest order in α, they do not decay strongly, although they can be produced in pairs through strong interactions. The allowed decay modes are :

$$\Psi^* \to q + \gamma$$

and

$$\Psi^* \to q + (f_1\bar{f}_2)$$

It is also found that the case $I_w = 1$ implies the existence of two weak isotriplets, which couple to right handed light quarks with the same hypercharge. Thus there is a triplet $\vec{U}$ coupled only to u_R and a triplet $\vec{D}$ coupled only to d_R. As for the case of excited leptons, the high isospin assignments imply exotic charge values : one finds excited quarks of charge $+\frac{5}{3}$ and $-\frac{4}{3}$ both for $I_w = 1$ as well as for $I_w = \frac{3}{2}$.

The question arises as how to produce these quarks at $\bar{p}p$ colliders and what are their characteristic production signals. Fig.2 shows the typical diagrams which contribute to the production cross-section to lowest order in α. For the case in which they are lighter than the IVB, one can calculate the decay widths of Z_0 and W through these $I_w = 1, \frac{3}{2}$ excited states. Table IX shows these rates. In Figs.3a and 3b we have plotted the ratios

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

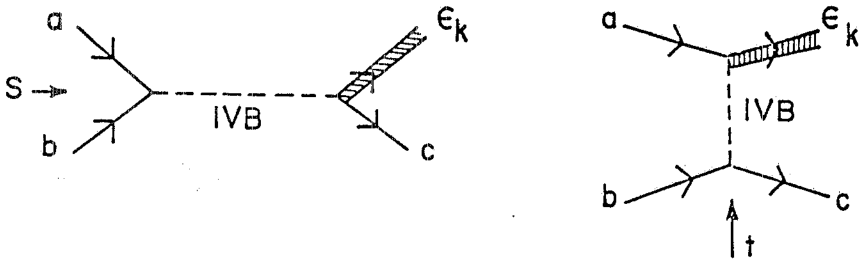


FIG. 2 - Diagrams contributing to the production of excited quarks through IVB's at hadron colliders.

TABLE IX - Decay width of Z_o and W^+ through $I_W = 1, 3/2$ excited quarks.

I_w	$\Gamma(Z_0 \to j_1 + j_2 + \gamma)$ [a]	$\Gamma(W^\pm \to j_1 + j_2 + \gamma)$	$\Gamma(W^\pm \to j_1 + j_2 + (f_1 \bar{f}_2)^+)$
1	$\frac{\alpha}{2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)\left(f_{1u}^2 + f_{1d}^2\right)\phi_Z$ [b]	0	$\frac{\alpha}{2}\left(\frac{f_{1u}^2 + f_{1d}^2}{\sin^2\theta_W}\right)B_{f_1\bar{f}_2}\phi_W$ [c]
3/2	$\frac{2\alpha}{3}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)f_{3q}^2\,\phi_Z$	$\frac{\alpha}{6}\left(\frac{f_{3q}^2}{\sin^2\theta_W}\right)\phi_W$	$\frac{\alpha}{2}\left(\frac{f_{3q}^2}{\sin^2\theta_W}\right)B_{f_1\bar{f}_2}\phi_W$

a) j_i refers to u or d jets

b) The phase space factor is given by

$$\phi_{IVB} = \left(2 + \frac{M_{IVB}^2}{\mu^2}\right)\left(1 - \frac{\mu^2}{M_{IVB}^2}\right)M_{IVB} .$$

c) The branching ratio $B_{f_1\bar{f}_2}$ counts the number of open fermionic channels.

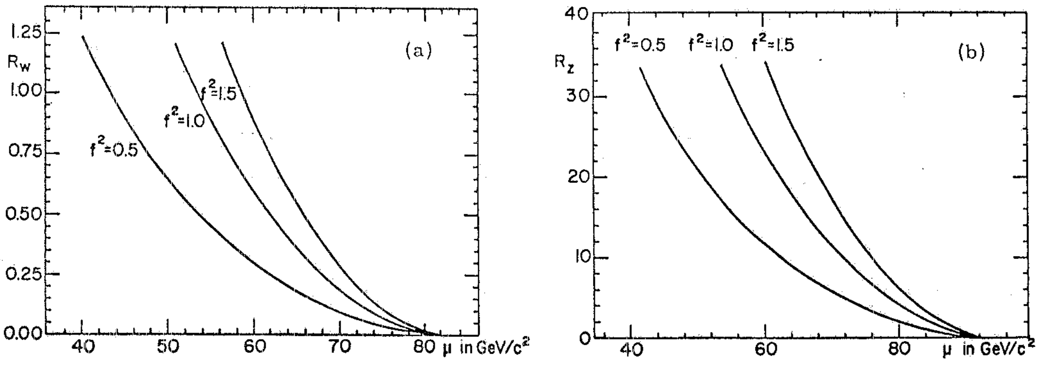


FIG. 3

and

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

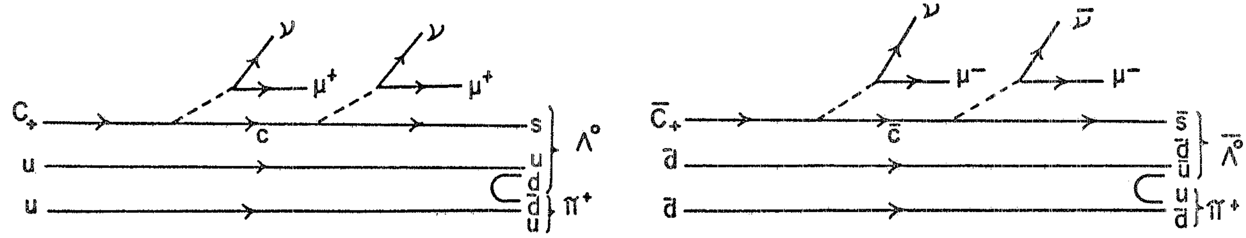
with $I_w = 1$, $B_{l+\nu} = \frac{1}{9}$ for different values of coupling constant $f^2 = f_{1u}^2 + f_{1d}^2$ and as a function of the mass μ. So far, however, there is no evidence that excited quarks with masses less than the IVB exist. Notice however that the process

$$p\bar{p} \to jet + \ jet + \ \gamma + X$$

is extremely hard to evaluate because of a difficult experimental background .

5. EXOTIC HADRONS

If excited quarks exist, one must also consider the possibility that baryons and mesons built with these quarks and with masses in the same range exist - and can be formed at the collider. For the case $I_w \geq 1$, the possibility of exotic hadrons with so far forbidden charge assignments, arises. One would observe exotic mesons of charge ± 2 and baryons with charge $+3$. How would they decay? In Figs.4a and 4b we show the possible decay of baryons made of an excited quark belonging to a hypothetical second family and two light quarks into an equal sign dimuon pair, a strange baryon and a π^+.



(a) $(C_+uu) \longrightarrow \mu^+\mu^+\Lambda^\circ\pi^+\nu\nu$

(b) $\overline{(C_+dd)} \longrightarrow \mu^-\mu^-\bar{\Lambda}^\circ\pi^+\bar{\nu}\bar{\nu}$

FIG. 4

6. CONCLUSION

The observation of anomalous Z-decays has spurred a number of theoretical speculations, of which we have described that related to the existence of excited quarks and leptons.

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