Turkish Journal of Physics

http://journals.tubitak.gov.tr/physics/

Research Article

Turk J Phys
(2018) 42: 235 – 241
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doi:10.3906/fiz-1710-28

A minimal fermion-scalar preonic model

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Received: 27.10.2017 • **Accepted/Published Online:** 09.04.2018 • **Final Version:** 01.06.2018

Abstract: A minimal fermion-scalar preonic model containing two fermionic preons and one scalar preon is proposed. This scheme allows prevention of the occurrence of undesired SM-level particles, namely leptons and quarks with unusual electric charges. Similar to the previous FS models, color-octet leptons and color-sextet quarks, which are expected to have masses much lower than the compositeness scale, are predicted. Observation of these particles could provide first indications of preonic models. The FCC/SppC pp option will give an opportunity to probe m_{q_6} up to 48/75 TeV and m_{l_8} up to 15/27 TeV within 1 year of operation at nominal luminosity. FCC/SppC based ep and μp colliders will essentially enlarge the covered mass region, namely m_{e_8} up to 23/27 TeV and m_{μ_8} up to 68/80 TeV.

Key words: Beyond the standard model, composite models, preons

1. Introduction

The structure of the atom was revealed by the famous Rutherford experiment, which was performed almost a century ago [1]. In the 1930s, the nucleus of the atom was discovered to be a bound state of protons and neutrons. Thus, a scientific basis was constructed for the periodical table of chemical elements. In the 1960s, high energy physics experiments showed that hadrons (including protons and neutrons) were also bound states of more fundamental particles: quarks [2–5]. Thanks to these experiments, the standard model (SM) was constituted, which seems to be in conformity with successful experiments in the TeV energy region [6]. On the other hand, many phenomena (such as family replication, fermion masses and mixings, left-right asymmetry, etc.) still cannot be explained by the SM. Several approaches reaching beyond the standard model (BSM) have been proposed in order to address these problems.

One of the promising branches of these BSM proposals is composite models of quarks and leptons. Existence of at least three fermion families and observation of the interfamily mixings of quarks and leptons support the idea of the existence of a more fundamental level of matter. Pati and Salam denoted these fundamental particles as preons. Historical arguments favoring preonic models are presented in Table 1 [7,8]. Composite models started to be developed from the 1970s (see [9] and references therein) and can be divided into two main subclasses: fermion-scalar (FS) and three fermion (FFF) models.

Even though there has not been any direct experimental evidence indicating a substructure of the SM fermions yet, mass patterns of fermion families and CKM mixings can be regarded as manifestations of the

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Table 1. Examples of "fundamental" substance "inflations" encountered in the last century.

Stages	1870s–1930s	1950s–1970s	1970s–2020s
Fundamental substance "inflation"	Chemical elements	Hadrons	Quarks & leptons
Systematic	Periodic table	Eight-fold way	Family replication
Confirmed predictions	New elements	New hadrons	l_8 and q_6?
Clarifying experiments	Rutherford [1]	SLAC DIS [2]	LHC? Or rather FCC?
Building blocks	Proton, neutron, electron	Quarks	Preons?
Energy scale	MeV	GeV	Multi-TeV?
Impact on technology	Exceptional	Indirect	Exceptional?

compositeness of these fermions. Future highest energy colliders such as FCC [10,11] and/or SPPC [12] with $\sqrt{s} = 100/136$ TeV, which are planned to be constructed in the 2030s, will enable us to investigate the new physics at the multi-TeV scale. Let us denote the new compositeness scale as Λ. A comparison between Λ and center of mass energies, $\sqrt{s}$, of future colliders points out our expectations from these colliders. If $\sqrt{s} \ll \Lambda$, compositeness induced contact four fermion interactions of SM particles have usually been considered, since one expects that the masses of new particles are in the order of Λ. If $\sqrt{s} > \Lambda$, interactions and particles of the new physics are expected to be revealed, and if this scheme is realized with future colliders, the expected results of these high energy collisions would vary by selected preonic models significantly. The compositeness scale of the new physics, Λ, is quite larger than the masses of SM fermions (m_{SM}). Currently there are three known mechanisms to satisfy the condition $m_{SM} \ll \Lambda$: chiral protection, quasi-Goldstone fermion mechanisms (for details, see [9] and references therein), and flavor democracy [13,14], which provides the opportunity to get the massless states as the superposition of initially massive particles and therefore gives an opportunity to handle 'massless' composite objects within preonic models. The true protection mechanism, either one of the abovementioned or a currently unknown mechanism, will be clarified after the discovery of preonic dynamics.

Commonly, FS models up to now include two fermionic and two scalar preons. In this work, in a belief of minimality at the ultimate fundamental physics scale, we show that it is possible to set a more economic preonic model containing two fermions and one scalar. In Section 2, conventional (2 fermion, 2 scalar) preon models are given with a short summary. In Section 3, the preonic set of the current study is presented. Afterwards, predicted SM-level exotic particles are described in Section 4 and finally final concluding remarks are given in a short summary in Section 5.

2. Fermion-scalar models

FS type composite models were proposed 40 years ago [15–17]. Most FS preonic models assume the existence of two fermionic and two scalar preons. Below we assume that preons are color triplets. In this case, color singlet SM leptons are predicted to be bound states of one fermionic preon and one scalar anti-preon:

$$l = \left(F\bar{S}\right) = 1 \oplus 8,$$

with a color-octet partner l_8. Quarks are expected to be composed of one fermionic and one scalar anti-preon in a similar manner:

$$q = \left(\bar{F}\bar{S}\right) = 3 \oplus \bar{6},$$

which means that each SM quark has one anti-sextet partner $\bar{q}_6$.

The first SM family fermions are given as:

$$\nu_e = \left(F_1\bar{S}_1\right) \quad e = \left(F_2\bar{S}_1\right) \quad d = \left(\bar{F}_1\bar{S}_2\right) \quad u = \left(\bar{F}_2\bar{S}_2\right).$$

Table 2 presents possible electric charge set schemes under an assumption $|Q_{F,S}| \leq 1$ [18]. The third column (Model III) of the table corresponds to the Fritzsch–Mandelbaum model [19] and the option given in the fourth column (Model IV) implies the FS symmetry from an electric charge viewpoint, which may be an indication of supersymmetry at the preonic level.

Table 2. Electric charges of scalar and fermionic preons.

Preons	Electric charges				
	Model I	Model II	Model III	Model IV	Model V
F_1	0	1/3	1/2	2/3	1
F_2	–1	–2/3	–1/2	–1/3	0
S_1	0	1/3	1/2	2/3	1
S_2	1/3	0	–1/6	–1/3	–2/3

One of the main problems of conventional FS models is some undesirable predicted SM-level particles that have not been observed yet. For example, the particles below are predicted in addition to the first SM family fermions: color singlets,

$$\left(F_1\bar{S}_2\right) \text{ and } \left(F_2\bar{S}_2\right),$$

and color triplets,

$$\left(\bar{F}_1\bar{S}_1\right) \text{ and } \left(\bar{F}_2\bar{S}_1\right).$$

The electric charges of these new particles are presented in Table 3.

Table 3. Electric charges of the additional undesired fermions corresponding to the preonic sets given in Table 2.

Additional particles	Electric charges				
	Model I	Model II	Model III	Model IV	Model V
$\left(F_1\bar{S}_2\right)$	–1/3	1/3	2/3	1	5/3
$\left(F_2\bar{S}_2\right)$	–4/3	–2/3	–1/3	0	2/3
$\left(\bar{F}_1\bar{S}_1\right)$	0	–2/3	–1	–4/3	–2
$\left(\bar{F}_2\bar{S}_1\right)$	1	1/3	0	–1/3	–1

There is no reason for these additional particles to be absent and to have masses far above the SM scale. Fritzsch and Mandelbaum proposed QED- or QCD-like preon dynamics (hypercolor) that resolves this problem [19]: repulsive interactions between preons with the same hypercolor charges prevent these undesired bound states. However, in their model, S_1 is a color anti-triplet, whereas F_1, F_2, and S_2 are color triplets. Moreover, preon dynamics need not be QED- or QCD-like. For example, 'gravitation-like' dynamics involves an attractive force only.

3. A minimal fermion-scalar model

In this study, considering the problem above, we propose a novel minimal FS model that prevents the occurrence of undesired SM-level particles. The proposed preons and their color, charge, and spins are given in Table 4. It should be noted that the electric charge set is unique, while in nonminimal models there are 5 choices (see Table 2).

Table 4. Color, charge, and spins of minimal FS model preons.

	Color (C)	Charge (Q)	Spin (S)
F_1	3	1/6	1/2
F_2	3	–5/6	1/2
S	3	1/6	0

In this case, bound states of fermionic preons with the scalar preon constitute the first SM family fermions as below.

$$Q_{F_1} + Q_{\bar{S}} = 0,\ C_{F_1} \otimes C_{\bar{S}} = \ 3 \otimes \bar{3} = 1 \oplus 8 \ \rightarrow \ \nu_e \equiv F_1\bar{S}$$

$$Q_{F_2} + Q_{\bar{S}} = -1,\ C_{F_2} \otimes C_{\bar{S}} = \ 3 \otimes \bar{3} = 1 \oplus 8 \ \rightarrow \ e \equiv F_2\bar{S}$$

$$Q_{\bar{F}_1} + Q_{\bar{S}} = -1/3,\ C_{\bar{F}_1} \otimes C_{\bar{S}} = \ \bar{3} \otimes \bar{3} = 3 \oplus \bar{6} \ \rightarrow \ d \equiv \bar{F}_1\bar{S}$$

$$Q_{\bar{F}_2} + Q_{\bar{S}} = 2/3,\ C_{\bar{F}_2} \otimes C_{\bar{S}} = \ \bar{3} \otimes \bar{3} = 3 \oplus \bar{6} \ \rightarrow \ u \equiv \bar{F}_2\bar{S}$$

One should note that the model still predicts color octet leptons and color sextet quarks.

Preons in FS models are color triplets, which means QCD is realized at the preonic level. If the space-time structure is not changed, it is natural to assume that electro-weak gauge symmetry is also realized at the preonic level. We present weak iso-spin and weak hypercharge values for preons in Table 5 for this reason.

Table 5. Weak iso-spin and weak hypercharge quantum numbers for preons corresponding to Table 4 regarding chirality of preonic level fermions.

	Weak isotopic charge (I_3)	Weak hypercharge (Y)
$\begin{pmatrix} F_{1_L} \\ F_{2_L} \end{pmatrix}$	1/2 –1/2	–2/3
F_{1_R}	0	1/3
F_{2_R}	0	–5/3
S	0	1/3

Another important issue is related to family replication. As mentioned in Section 1, the mass pattern of fermion families is another indication of substructure(s) at a more fundamental level. The second and the third SM fermion families can be constructed by quantum pair excitations [20]. For example, second family fermions may be constructed by addition of $(S\bar{S})$ to the first family fermions as follows.

$$\nu_\mu \equiv (F_1\bar{S})(S\bar{S}) \quad \mu \equiv (F_2\bar{S})(S\bar{S}) \quad s \equiv (\bar{F}_1\bar{S})(S\bar{S}) \quad c \equiv (\bar{F}_2\bar{S})(S\bar{S})$$

In a similar manner the third family can be expressed as follows.

$$\nu_\tau \equiv (F_1\bar{S})(S\bar{S})^2 \quad \tau \equiv (F_2\bar{S})(S\bar{S})^2 \quad b \equiv (\bar{F}_1\bar{S})(S\bar{S})^2 \quad t \equiv (\bar{F}_2\bar{S})(S\bar{S})^2$$

In the structures above, we assume that only the singlet component of $(S\bar{S})$ takes part in formation of the second and the third SM family fermions. Alternatively, one can consider the case when the color octet component of $(S\bar{S})$ is also included in the formation of the upper families. In this case, $(F\bar{S})(S\bar{S})$ has following color structure:

$$(1 \oplus 8) \otimes (1 \oplus 8) = 1 \oplus 8 \oplus 8 \oplus 1 \oplus 8 \oplus 8 \oplus 10 \oplus \bar{10} \oplus 27.$$

Therefore, one can identify the first singlet as μ and the second singlet as τ. As a result, the muon has two color octet partners, whereas the τ lepton has two octet, one decuplet, one anti-decuplet, and one 27-plet partners. The same decomposition takes place for ν_μ and ν_τ.

It should be mentioned that the proposed minimal model contains a triangle anomaly, as do the FS models in general, which in principle can be eliminated by introducing mirror fermionic preons.

4. Color-octet leptons and color-sextet quarks

All the preonic FS models predict color-octet leptons, l_8, and color-sextet quarks, q_6. $SU_W(2) \times U_Y(1)$ structures of l_8 and $\bar{q}_6$ coincide with those of l and q, respectively. Therefore, the chirality protection mechanism, which keeps the SM fermions' masses small, is also assumed to be valid for l_8 and q_6, such that m_{l_8}, $m_{q_6} \ll \Lambda$. Let us mention that masses of the vector and scalar bound states (including leptoquarks) are expected to be at the order of Λ. Therefore, discovery of l_8 and q_6 with future high energy colliders may provide a first confirmation of preonic models.

Production, signatures, and discovery limits of color-sextet quarks and color-octet leptons at the LHC were roughly considered in [18]. In recent papers [21–24], l_8 production at the LHC was analyzed in detail: it was shown that m_{l_8} 1.2 TeV is excluded by current ATLAS/CMS data and future LHC runs will cover m_{l_8} up to 2.5–3 TeV. Certainly, future 100 TeV center of mass energy *pp* colliders, FCC and/or SppC, have a great potential for BSM physics searches. In Table 6 we present the discovery limits for resonant q_6 and pair l_8 production at these colliders [18]. Discovery mass limit values for the FCC and SppC are obtained by rescaling LHC results using the method developed by Salam and Weiler [25].

Table 6. Discovery (5σ) limits for q_6 and l_8 at future *pp* colliders.

Collider	$\sqrt{s}$, TeV	L_{int}, per year	m_{l_8}, TeV	m_{q_6}, TeV
LHC	14	100 fb^{-1}	3	8
FCC	100	500 fb^{-1}	15	48
SppC	136	10,000 fb^{-1}	27	75

Resonant l_8 production could be investigated at the FCC and SppC based energy frontier *lp* colliders (for main parameters of FCC-*lp* and SppC-*lp* see [26] and [27], respectively). Potential of FCC-*ep* for e_8 search was analyzed in [8], and similar analysis for μ_8 at FCC-μp was performed in [28]. Discovery limit results are summarized in Tables 7 and 8, respectively.

5. Conclusion

In this study, we propose a novel FS composite model to form SM fermions from the preonic level while assuming SM bosons as fundamental. By means of the minimal approach of the model, FS bound states are constructed by only three preonic-level particles, namely 2 fermionic preons and 1 scalar preon. This scheme has two essential

Table 7. Discovery (5σ) limits for e_8 at FCC/SppC based (E_p = 50/68 TeV) *ep* colliders [23,24].

E_e, GeV	$\sqrt{s}$, TeV	L_{int}, per year	m_{e_8}, TeV
60	3.46/4.04	100 fb^{-1}	2.9/3.3
500	10.0/11.7	10 fb^{-1}	8.1/9.4
		100 fb^{-1}	8.6/10.0
5000	31.6/36.9	1 fb^{-1}	20.1/23.4
		10 fb^{-1}	23.1/26.9

Table 8. Discovery (5σ) limits for μ_8 at FCC/SppC based (E_p = 50/68 TeV) μp colliders [25].

E_μ, GeV	$\sqrt{s}$, TeV	L_{int}, per year	m_{μ_8}, TeV
750	12.2/14.3	5/12 fb^{-1}	9.21/12.1
1500	17.3/20.2	5/43 fb^{-1}	13.2/20.2
20,000	63.2/73.8	10 fb^{-1}	41.5/48.5
50,000	100/117	10 fb^{-1}	68.4/80

advantages compared to standard FS models with two fermionic and two scalar preons: it constructs SM leptons and quarks in a unique way and allows prevention of the occurrence of undesired SM-level particles, namely leptons and quarks with unusual electric charges. Similar to the previous FS models, color-octet leptons and color-sextet quarks, which are expected to have masses much lower than the compositeness scale, are predicted. Observation of these particles could provide first indications of preonic models. The FCC (SppC) *pp* option will provide an opportunity to probe m_{q_6} up to 48 (75) TeV and m_{l_8} up to 15 (27) TeV within 1 year of operation at nominal luminosity. FCC/SppC based *ep* and μp colliders will essentially enlarge the covered mass region for color octet leptons, namely m_{e_8} up to 23/27 TeV and m_{μ_8} up to 68/80 TeV.

Acknowledgment

This study was supported by TÜBİTAK under Grant No. 114F337.

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