A Minimal Fermion-Scalar Preonic Model

U. Kaya
*Department of Physics, Faculty of Sciences, Ankara University, Ankara, Turkey*

B. B. Oner
†Department of Material Science and Nanotechnology, TOBB University of Economics and Technology, Ankara, Turkey

S. Sultansoy
‡TOBB University of Economics and Technology, Ankara, Turkey and ANAS Institute of Physics, Baku, Azerbaijan

A minimal fermion-scalar preonic model containing two fermionic and one scalar preons is proposed. This scheme allows to prevent 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. FCC/SppC pp option will give opportunity to probe $m_{\nu_e}$ up to 48/75 TeV and $m_{\tau}$ up to 15/27 TeV within one year operation at nominal luminosity. FCC/SppC based ep and $\mu p$ colliders will essentially enlarge covered mass region, namely, $m_{e\nu}$ up to 23/27 TeV and $m_{\mu\tau}$ up to 68/80 TeV.

*ukaya@etu.edu.tr  †b.oner@etu.edu.tr  ‡ssultansoy@etu.edu.tr*
I. INTRODUCTION

Structure of the atom has been revealed by the famous Rutherford experiment which was performed almost a century ago [1]. In 1930s, the nucleus of the atom is discovered to be a bound state of protons and neutrons. Thus, a scientific basis have been constructed for Periodical Table of chemical elements. In 1960s, high energy physics experiments showed that hadrons (including protons and neutrons) were also bound states of more fundamental particles: quarks [2]. Thanks to these experiments, Standard Model (SM) was constituted which seems to be in conformity with succeeding experiments in \( \lesssim \) TeV energy region [3]. On the other hand, a lot of phenomena (such as family replication, fermion masses and mixings, left-right asymmetry etc.) still can not 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 inter-family mixings of quarks and leptons support the idea of the existence of a more fundamental level of matter. Pati and Salam have denoted these fundamental particles as preons. Historical arguments favoring preonic models are presented in Table I [4, 5]. Composite models started to be developed from 1970s (see [6] and references therein) and can be divided into two main subclasses: fermion-scalar (FS) and three fermion (FFF) models.

Even though there have not been any direct experimental evidence indicating a substructure of the SM fermions yet, mass pattern of fermion families and CKM mixings can be regarded as a manifestation of compositeness of these fermions. Future high energy colliders such as FCC [7, 8] and/or SPPC [9] with \( \sqrt{s} = 100/136 \) TeV, which are planned to be constructed in 2030s, will enable us to investigate the new physics at the multi-TeV scale. Let us denote the new compositeness scale as \( \Lambda \). A comparison between \( \Lambda \) 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 lay in the order of \( \Lambda \). If \( \sqrt{s} > \Lambda \), interactions and particles of the new physics are expected to be revealed and if this scheme will be realized at future colliders, expected results of these high energy collisions would vary by a selected preonic model heavily. The compositeness scale of the new physics, \( \Lambda \), is quietly 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 [6] and references therein), as well as flavor democracy [10, 11] (which provides the opportunity to get the massless states as the superposition of initially massive particles and, therefore, gives opportunity to handle "massless" composite objects within preonic models). The true protection mechanism, either one of the abovementioned or currently unknown mechanism, will be clarified after the discovery of preonic dynamics.

Commonly, fermion-scalar 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 II conventional (2 fermion, 2 scalar) preon models are given with a short summary. In Section III, preonic set of the current study is presented. Afterwards, predicted SM-level exotic particles are described in Section IV and finally conclusion/final remarks are given in a short summary in Section V.

| Fundamental Particle Inflation | Stages | Chemical Elements | Hadrons | Quarks & Leptons |
|-------------------------------|--------|-------------------|---------|-----------------|
| Systematic                    | 1870s-1930s | Periodic Table | Eight-fold Way | Family Replication |
| Confirmed Predictions         | 1950s-1970s | New Elements | New Hadrons | \( t_s \) and \( q_b \) |
| Clarifying Experiments        | 1970s-2020s | Rutherford | SLAC DIS | LHC? or rather FCC? |
| Building Blocks               |        | Proton, Neutron, Electron | Quarks | Preons |
| Energy Scale                  |        | MeV | GeV | Multi-TeV |
| Impact on Technology          |        | Exceptional | Indirect | Exceptional |

II. FERMION-SCALAR MODELS

Fermion-scalar (FS) type composite models were proposed forty years ago [12-14]. Most of FS preonic models assume 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.
3 with a color-octet partner $l_8$. Quarks are expected to be composed of one fermionic and one scalar anti-preons in a similar manner

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

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

The first SM family fermions are given as

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

Table II represents possible electric charge set schemes under an assumption $|Q_{F,S} \leq 1 |$ [15]. The third column (Model III) set of the table corresponds to Fritzsch-Mandelbaum model [16] and the option given in the fourth column (Model IV) implies the fermion-scalar symmetry from electric charge viewpoint which may be indication of super-symmetry at preonic level.

| Preons | Electric Charges | Model I | Model II | Model III | Model IV | Model V |
|--------|------------------|---------|----------|-----------|----------|---------|
| $F_1$  | 0                | 1/3     | 1/2      | 2/3       | 1        |         |
| $S_1$  | 0                | 1/3     | 1/2      | 2/3       | 1        |         |
| $F_2$  | -1               | -2/3    | -1/2     | -1/3      | 0        |         |
| $S_2$  | 1/3              | 0       | -1/6     | -1/3      | -2/3     |         |

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

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

and color triplets

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

Electric charges of these new particles are presented in Table III.

| Additional Particles | Electric Charges | Model I | Model II | Model III | Model IV | Model V |
|----------------------|------------------|---------|----------|-----------|----------|---------|
| $(F_1 \bar{S}_2)$    | -1/3             | 1/3     | 2/3      | 1         | 5/3      |         |
| $(F_2 \bar{S}_2)$    | -4/3             | -2/3    | -1/3     | 0         | 2/3      |         |
| $(\bar{F}_1 \bar{S}_1)$ | 0          | -2/3    | -1       | -4/3      | -2       |         |
| $(\bar{F}_2 \bar{S}_1)$ | 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 \cite{16}: repulsive interactions between preons with the same hypercolor charges prevent these undesired bound states. However, in their model, $S_1$ is color anti-triplet, whereas $F_1$, $F_2$ and $S_2$ are color triplets. Moreover, preon dynamics need not to be QED- or QCD-like. For example, “gravitation-like” dynamics involve attractive force only.

### III. A MINIMAL FERMION-SCALAR MODEL

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

| 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:

\[
Q_{F_1} + Q_S = 0, \quad C_{F_1} \otimes C_S = 3 \otimes \bar{3} = 1 \oplus 8 \quad \rightarrow \quad \nu_e \equiv (F_1 \bar{S})
\]

\[
Q_{F_2} + Q_S = -1, \quad C_{F_2} \otimes C_S = 3 \otimes \bar{3} = 1 \oplus 8 \quad \rightarrow \quad e \equiv (F_2 \bar{S})
\]

\[
Q_{F_1} + Q_S = -1/3, \quad C_{\bar{F}_1} \otimes C_S = \bar{3} \otimes \bar{3} = 3 \oplus \bar{6} \quad \rightarrow \quad \bar{d} \equiv (\bar{F}_1 \bar{S})
\]

\[
Q_{F_2} + Q_S = 2/3, \quad C_{\bar{F}_2} \otimes C_S = \bar{3} \otimes \bar{3} = 3 \oplus \bar{6} \quad \rightarrow \quad \bar{u} \equiv (\bar{F}_2 \bar{S})
\]

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

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

| Weak Isotopic Charge ($I_3$) | Weak Hypercharge ($Y$) |
|-----------------------------|------------------------|
| $F_{1L}$                    | $1/2$                  | $-2/3$                |
| $F_{2L}$                    | $-1/2$                 |                        |
| $F_{1R}$                    | 0                      | $1/3$                 |
| $F_{2R}$                    | 0                      | $-5/3$                |
| $S$                         | 0                      | $1/3$                 |

Another important issue is related with family replication. As mentioned in the Introduction, 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 \cite{17}. For example, second family fermions may be constructed by addition of $(S\bar{S})$ to first family fermions:

\[
\nu_\mu \equiv (F_1 \bar{S})(S\bar{S})
\]

\[
\mu \equiv (F_2 \bar{S})(S\bar{S})
\]
shown that $m$ for BSM physics search. In Table VI we present discovery limits for resonant $l$ roughly considered in \cite{15}. In recent papers \cite{18–21}, $l$ parameters of FCC-colliders. Therefore, discovery of $l$ and $\mu$ in Table VII and VIII, respectively.

Therefore, one can identify the first singlet as $\mu$ and the second singlet as $\tau$. As a result, muon has two color octet partners, whereas $\tau$ lepton has two octet, one decuplet, one anti-decuplet and one 27-plet partners. The same decomposition takes place for $\nu_\mu$ and $\nu_\tau$.

IV. COLOR-OCTET LEPTONS AND COLOR-SEXET QUARKS

All of the preonic FS models predict color-octet leptons, $l_8$, and color-sexet quarks, $q_6$. $SU_W(2) \times U_Y(1)$ structures of $l_8$ and $\bar{q}_6$ are coincide with that of $l$ and $q$, respectively. Therefore, chirality protection mechanism, which keeps 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 $\Lambda$. Therefore, discovery of $l_8$ and $q_6$ at 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 have been analyzed in details: it is shown that $m_{l_8} \lesssim 1.2$ TeV is excluded by current ATLAS/CMS data and future LHC runs will cover $m_{l_8}$ up to $2.5\pm3$ TeV. Certainly, future 100 TeV center of mass $pp$ colliders, FCC and/or SppC, have a great potential for BSM physics search. In Table VI we present discovery limits for resonant $q_6$ and pair $l_8$ production at these colliders.

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 \cite{22} and \cite{23}, respectively). Potential of FCC-$ep$ for $e_8$ search has been analyzed in \cite{24}, similar analysis for $\mu_8$ at FCC-$\mu p$ have been performed in \cite{25}. Discovery limits results are summarized in Table VII and VIII, respectively.

| 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             | 10000 fb$^{-1}$   | 27             | 75             |

Table VII. Discovery (5$\sigma$) limits for $e_8$ at FCC/SppC based ($E_p = 50/68$ TeV) $ep$ colliders.

| $E_{c}$, 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        |
| 5000         | 31.6/36.9       | 1 fb$^{-1}$       | 20.1/23.4      |
|              |                 | 10 fb$^{-1}$      | 23.1/26.9      |
Table VIII. Discovery (5σ) limits for $\mu_8$ at FCC/SppC based ($E_p = 50/68$ TeV) $pp$ colliders.

| $E_\mu$, GeV | $\sqrt{s}$, TeV | $L_{int}$ per year | $M_{\mu_8}$, 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       |
| 20000        | 63.2/73.8       | 10 $fb^{-1}$     | 41.5/48.5       |
| 50000        | 100/117         | 10 $fb^{-1}$     | 68.4/80         |

V. CONCLUSION

In this study, we propose a novel fermion-scalar composite model to form SM fermions from preonic level while assuming SM bosons as fundamental. By means of the minimal approach of the model, fermion-scalar bound states are constructed by only three preonic-level particles, namely 2 fermionic and 1 scalar preons. This scheme allows to prevent 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-sexet 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. FCC (SppC) $pp$ option will provide opportunity to probe $m_{\mu_8}$ up to 48 (75) TeV and $m_{e_8}$ up to 15 (27) TeV within one year operation at nominal luminosity. FCC/SppC based $e\bar{p}$ and $\mu p$ colliders will essentially enlarge covered mass region, namely, $m_{e_8}$ up to 23/27 TeV and $m_{\mu_8}$ up to 68/80 TeV.

ACKNOWLEDGMENTS

This study is supported by TUBITAK under the grant no 114F337.

[1] E. Rutherford, "LXXIX. The scattering of $\alpha$ and $\beta$ particles by matter and the structure of the atom", The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 21.125 (1911): 669-688.
[2] J.I. Friedman and H.W. Kendall, Annu. Rev. Nucl. Sci. 22, 203 (1972); Corresponding Nobel lectures: R.E. Taylor, Rev. Mod. Phys. 63, 573 (1991); H.W. Kendall, ibid., p. 597; J.I. Friedman, ibid., p. 615.
[3] [http://pdg.lbl.gov](http://pdg.lbl.gov)
[4] M. Sahn, S. Sultansoy, and S. Turkoz, “Search for the fourth standard model family”, Physical Review D 83, no. 5 (2011): 054022.
[5] Y.C. Acar, U. Kaya, B. B. Oner, and S. Sultansoy, “Color octet electron search potential of FCC based $e\bar{p}$ colliders”, Journal of Physics G: Nuclear and Particle Physics 44(4), 045005 (2017); arXiv:1605.08028v2 [hep-ph].
[6] I.A.D’ Souza, C.S. Kalman, “PREONS: Models of leptons, quarks and gauge bosons as composite objects, World Scientific Publishing Co”, (1992).
[7] FCC web site, [https://fcc.web.cern.ch](https://fcc.web.cern.ch).
[8] M. Benedikt and F. Zimmermann, “Towards Future Circular Colliders”, J. Korean Phys. Soc. 69 (2016) 893-902.
[9] F. Su et al. “SPPC Parameter Choice and Lattice Design”, 7th International Particle Accelerator Conference (IPAC’16), Busan, Korea, May 8-13, 2016. JACOW, Geneva, Switzerland, 2016.
[10] S. Sultansoy, “Flavor democracy in particle physics”, In AIP Conference Proceedings, vol. 899, no. 1, pp. 49-52. AIP, 2007; arXiv: [hep-ph/0610279](http://arxiv.org/abs/hep-ph/0610279) (2006).
[11] S. Sultansoy, “Three remarks on the MSSM”, arXiv: [hep-ph/0003269](http://arxiv.org/abs/hep-ph/0003269) (2000).
[12] K. Matumoto, “On a composite model for hadronic constituents”, Prog. Theor. Phys. 52, 1973 (1974).
[13] O.W. Greenberg, “New narrow resonances and separate localization of ordinary and color SU (3)”, Phys. Rev. Lett. 35, 1120 (1975).
[14] H. Terazawa, “Subquark model of leptons and quarks”, Phys. Rev. D 22, 184 (1980).
[15] A. Celikel, M. Kantar, and S. Sultansoy, “A search for sextet quarks and leptoquarks at the LHC”, Physics Letters B 443.1 (1998): 359-364.
[16] H. Fritzsch, and G. Mandelbaum, “Weak interactions as manifestations of the substructure of leptons and quarks”, Physics Letters B 102, no. 5 (1981): 319-322.
[17] J.C. Pati and A. Salam, “Supersymmetry at the preonic or pre-preonic level and composite supergravity”, Nuclear Physics B 214, no. 1 (1983): 109-135.
[18] T. Mandal and S. Mitra, “Probing color octet electrons at the LHC”, Phys. Rev. D 87 (2013) 095008.
[19] D. Gonçalves-Netto et al., “Looking for leptoquarks”, Phys. Rev. D 87 (2013) 094023.
[20] T. Jelinski and D. Zhuridov, “Leptoquarks in dilepton production at LHC”, Acta Phys.Polon. B46 (2015) no.11, 2185; arXiv:1510.04872 [hep-ph].
[21] T. Mandal, S. Mitra, and S. Seth. “Probing compositeness with the CMS eejj & eej data” Physics Letters B 758 (2016): 219-225; arXiv:1602.01273v1

[22] Y.C. Acar et al. “Future circular collider based lepton-hadron and photon-hadron colliders: luminosity and physics”, Nucl. Instrum. Meth. A 871 (2017), 47-53; arXiv:1608.02190v3 [physics.acc-ph].

[23] A.C. Canbay et al. “SppC based energy frontier lepton-proton colliders: luminosity and physics”, Adv. High Energy Phys. vol. 2017, Article ID 4021493, 6 pages, 2017. doi:10.1155/2017/4021493; arXiv:1704.03534v3 [physics.acc-ph].

[24] Y.C. Acar, U. Kaya, B. B. Oner, “Resonant production of color octet muons at the future circular collider based muon-proton colliders”, arXiv:1703.04030v2 [hep-ph].