Are there indications of compositeness of leptons and quarks in CERN LEP data?

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The "preon-trinity" model for the compositeness of leptons, quarks and heavy vector bosons predicts several new heavy leptons and quarks. Three of them can be produced in e^+e^- annihilations at CERN LEP energies, since they can be created out of a system of three preons and their antipreons, where three preons form a heavy lepton or quark, while the other three go into a normal lepton or quark. In fact, these new particles are predicted to be lighter than the top quark, while the top itself cannot be produced this way, due to its particular preon substructure. The empirical situation is analyzed, and the most likely masses are estimated.

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I. INTRODUCTION

New generations of leptons and quarks, as compared with those prescribed by the so-called standard model (SM), have been searched for at the three main high-energy laboratories, *i.e.*, CERN LEP, DESY HERA and the Fermilab Tevatron. A general conclusion is that no statistically significant signals have been found [1]. This goes for both a fourth generation of leptons and quarks, *e.g.*, a b' quark, and excited versions of the normal ones, *e.g.*, e^* and ν^*. From an experimental point of view there is not much difference between the two approaches. A fourth generation is believed to mimic the normal three, while excited leptons and quarks are believed to couple to other particles exactly like the unexcited versions, except for kinematic effects of the higher masses.

The existence of any of these would be a strong evidence for a substructure of leptons and quarks in terms of preons. Excitations are hard to imagine without an inner structure of the excited object, and yet another generation of leptons and quarks would also be difficult to reconcile with the idea that they are all fundamental.

There are indeed already several phenomenological, and logical, arguments in favour of a substructure of leptons, quarks and heavy vector mesons in terms of preons [2, 3, 4]. It even seems as if the standard model itself contains several prophecies of preons [3] among its many seemingly unrelated bits and pieces. The "preon-trinity" model [5] was inspired by such arguments, as well as by models for the three-quark structure of light baryons [6, 7], by early preon models [2, 8, 9, 10] and by the concept of diquarks [11].

The aim of this publication is to reanalyze the data from, above all, the (closed) CERN LEP facility, in order to look for signals of new leptons and quarks, as prescribed by the preon-trinity model. As it turns out, some of the criteria used in the existing experimental searches are not valid in the model. Above all, the predicted new leptons and quarks are *not* just heavier versions of the old ones. They have their own unique features, which should be confronted with the data.

TABLE I: The "supersymmetric" preon scheme.

charge	$+e/3$	$-2e/3$	$+e/3$
spin-1/2 preons	α	β	δ
spin-0 (anti-)dipreons	$(\bar{\beta}\bar{\delta})$	$(\bar{\alpha}\bar{\delta})$	$(\bar{\alpha}\bar{\beta})$

II. THE MODEL

The main ingredients are that there exist three absolutely stable species (flavours) of spin-1/2 preons, called α, β and δ, with electric and colour charges, and that these also tend to form tightly bound spin-0 dipreons. Thanks to the choice of preon charges, inspired by the ones of the original three-quark model, the scheme gets an attractive supersymmetric balance between preons and *anti*-dipreons, as summarised in Table I.

It is then prescribed that leptons are built up by one preon and one dipreon. Quarks consist of one preon and one anti-dipreon, and heavy vector bosons of one preon and one antipreon. The results are shown in Table II. There is an obvious $SU(3)$ preon-flavour symmetry in the scheme, just like with quark flavours in the first quark model. The stability of preons means that the total preon flavour is absolutely conserved, unlike the quark flavour in the quark model.

One can make about a dozen observations about leptons, quarks and heavy vector bosons. Most of these provide qualitative explanations of some seemingly disjunct ingredients of the SM, *e.g.*, the mixings of some quarks, neutrinos and heavy vector bosons, and the (partial) conservation of three lepton numbers, all being consequences of preon flavour conservation [5].

The most notable difference from the SM is the set of new leptons, quarks and heavy vector bosons predicted

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TABLE II: Composite states in the preon model: *leptons* as a preon and a dipreon, *quarks* as a preon and an anti-dipreon, and *heavy vector bosons* as a preon and an antipreon.

	$(\beta\delta)$	$(\alpha\delta)$	$(\alpha\beta)$	$(\bar{\beta}\bar{\delta})$	$(\bar{\alpha}\bar{\delta})$	$(\bar{\alpha}\bar{\beta})$	$\bar{\alpha}$	$\bar{\beta}$	$\bar{\delta}$
α	ν_e	μ^+	ν_τ	u	s	c	Z^0/Z'	W^+	Z^*
β	e^-	$\bar{\nu}_\mu$	τ^-	d	X	b	W^-	Z'/Z^0	W'^-
δ	$\nu_{\kappa 1}$	κ^+	$\nu_{\kappa 2}$	h	k	t	$\bar{Z}^*$	W'^+	Z''/Z'

by the model. These contain a δ preon that does not belong to a dipreon, and are to be found in the bottom row of Table II, plus in the right-most column. They must all have such high masses that they have escaped discovery, *except* the t quark, which is most probably the quark below b in Table II. This indicates that also the other new quarks and leptons have masses in the region $100-200$ GeV. There is a good chance that $\nu_{\kappa 1}$, κ, $\nu_{\kappa 2}$, h and k (earlier called "g" [5]) are all *lighter* than the top quark. It must be stressed though that the model is entirely defined by this scheme, and has not (yet) been complemented with a preon dynamics. Hence exact masses, branching ratios and life-times of quarks and leptons cannot be reproduced or predicted. However, experience tells that lepton masses are lower than that of "corresponding" quarks. In addition, there is a trend among the known quarks of Table II that the masses increase from left to right. All in all, one can therefore expect the mass relations $M_{\nu_{\kappa 1}} < M_{\nu_{\kappa 2}} < M_t$, $M_h < M_k < M_t$, and $M_\kappa < M_k$, which means that CERN LEP energies would suffice for the reactions discussed in this study, and that signs of compositeness might hence exist in old data.

In the following, only the relevance of the model to existing data from the CERN LEP facility will be discussed. For other details of the model, such as the argument that the odd X quark, with charge $-4e/3$, is not expected to exist as a bound system, the reader is referred to Ref. [5]. General arguments that preons should exist are given in Refs. [2, 3].

III. THE REACTIONS

Any system of a certain preon flavour and its antiflavour can be produced in e^+e^- annihilation, as long as the energy suffices. As can be seen in Table II, there are three new leptons/quarks that carry the same net preon flavour as a lighter partner. These pairs are $\nu_{\kappa 2} = \delta(\alpha\beta) \leftrightarrow \nu_e = \alpha(\beta\delta) \leftrightarrow \bar{\nu}_\mu = \beta(\alpha\delta)$, $h = \delta(\bar{\beta}\bar{\delta}) \leftrightarrow c = \alpha(\bar{\alpha}\bar{\beta})$ and $k = \delta(\bar{\alpha}\bar{\delta}) \leftrightarrow b = \beta(\bar{\alpha}\bar{\beta})$.

As long as the masses of these leptons and quarks are not too high, e^+e^- annihilation can therefore result in the production of the pairs $\nu_{\kappa 2}\bar{\nu}_e$, $\nu_{\kappa 2}\nu_\mu$, $h\bar{c}$ and $k\bar{b}$:

$$e^+e^- \to \delta(\alpha\beta) + \bar{\alpha}(\bar{\beta}\bar{\delta}) = \nu_{\kappa 2} + \bar{\nu}_e, \tag{1}$$

$$e^+e^- \to \delta(\alpha\beta) + \bar{\beta}(\bar{\alpha}\bar{\delta}) = \nu_{\kappa 2} + \nu_\mu, \tag{2}$$

$$e^+e^- \to \delta(\bar{\beta}\bar{\delta}) + \bar{\alpha}(\alpha\beta) = h + \bar{c}, \tag{3}$$

and

$$e^+e^- \to \delta(\bar{\alpha}\bar{\delta}) + \bar{\beta}(\alpha\beta) = k + \bar{b}. \tag{4}$$

(and the corresponding antiparticles). For the sake of simplicity, reactions with additional particles in the final state, *e.g.*, photons, will not be discussed here. All final particles will hence be assumed to come from hadronisation or decay of the quarks or leptons listed above.

It is notable that the top quark, $t = \delta(\bar{\alpha}\bar{\beta})$, has no such partner, and hence there is no "single-top production" in e^+e^- reactions.

Since $e^- = \beta(\beta\delta)$, *all* processes of interest are transitions from the original preon system $\beta(\beta\delta)\bar{\beta}(\bar{\beta}\bar{\delta})$ to the intermediate one $\alpha\bar{\alpha}\beta\bar{\beta}\delta\bar{\delta}$. This, in turn, can split up in many different ways, among which are the four different pairs listed above.

The transition

$$e^+e^- = \beta(\beta\delta)\bar{\beta}(\bar{\beta}\bar{\delta}) \to S^* \to \alpha\bar{\alpha}\beta\bar{\beta}\delta\bar{\delta} \tag{5}$$

can take place via a number of intermediate systems S^*. Examples are one or more photons, a suitable combination of gluons (or "hypergluons"; the possible quantas of a hypothetical preon interaction [2]), a preon-antipreon pair ($\beta\bar{\beta}$, after the annihilation of $(\beta\delta)(\bar{\beta}\bar{\delta})$) or a dipreon-anti-dipreon pair ($(\beta\delta)(\bar{\beta}\bar{\delta})$, after the annihilation of $\beta\bar{\beta}$).

The latter should be less likely, because it seems as if a dipreon always stays together, once it has been created [5]. Hence the only new particles that can be produced from the annihilation of $\beta\bar{\beta}$ would be through the creation of a $\delta\bar{\delta}$ pair. This would result in either $e^+e^- \to \nu_{\kappa 1}\bar{\nu}_{\kappa 1}$ or $h\bar{h}$, with only superheavy final leptons or quarks. They can occur only if $M_{\kappa 1}, M_h < E_{LEP}/2$, where E_{LEP} is the total LEP energy ($\leq$ 209 GeV). In that case they might be seen through the decay products of the two neutrinos or quarks.

The model also allows for production processes like

$$e^+e^- \to \nu_e + \nu_\mu \tag{6}$$

(but *not* of different *charged* leptons, like $e^+\mu^-$). However, due to the neutrino helicities, this can happen only for annihilation in a total spin-0 state. Therefore, this final state cannot be produced in, *e.g.*, Z^0 decay, which means that it cannot be restricted by the well-known "three-generation" data from Z^0 decay [1]. However, the decay

$$Z^0 \to \bar{\nu}_e + \nu_{\kappa 2}, \tag{7}$$

should, in principle, be possible, and similarly for the final states with quarks in reactions (3) & (4). They have not been seen, so their masses must exceed $M_Z/2$.

IV. ANALYZING THE CERN LEP DATA

We will start by discussing the $\nu_{\kappa 2}$ decay channels of interest for an analysis of LEP data. It is important to keep in mind that lepton numbers are not exactly conserved in our model, and that there is no fourth lepton number connected to the predicted new leptons. The observed lepton number conservation is in our model equivalent to "dipreon number conservation", *i.e.*, the three usual lepton numbers are conserved in leptonic processes only to the extent that the tightly bound dipreons are left intact. In normal leptonic decays and "low-energy" reactions this must be the case, because all imaginable dipreon-breaking processes violate energy conservation. However, the heavy leptons *must* decay through a reshuffling of the preons inside a dipreon, and would hence change the normal lepton numbers. An example is $\kappa^+ \to \mu^+ + \nu_e + \bar{\nu}_\tau$, violating all three lepton numbers. In addition, the three neutrinos on the diagonal of Table II might mix into new mass eigenstates, since they have identical preon net flavours. This is equivalent to neutrino oscillations, which do not conserve lepton numbers. Lepton number conservation might also be violated in normal leptonic collisions, if the energy is high enough to break up existing dipreons. As argued in [5] we think that the energy scale for new preon processes is a few hundred GeV rather than TeV (as the top quark seems to be an example of a "superheavy" three-preon state). The "TeV scale" often mentioned in discussions of compositeness is rather the expected momentum-transfer scale for revealing substructure in deep-inelastic scattering of leptons and quarks.

The most interesting decay channel for the lightest heavy neutrino is

$$\nu_{\kappa 2} \to e^-/\mu^+ + W^{+/-}, \tag{8}$$

followed by

$$W \to q_1\bar{q}_2, \tag{9}$$

or in terms of preon processes:

$$\delta(\alpha\beta) \to \beta(\beta\delta)/\alpha(\alpha\delta) + (\alpha\bar{\beta})/(\bar{\alpha}\beta). \tag{10}$$

The decay into two quark jets gives an opportunity to find the invariant mass of the neutrino. The W is most probably real if the neutrino mass is reasonably well above the W mass. Hence one should restrict the analysis to events where the estimated invariant mass of the two hadron jets is close to the W mass. The main background to this process is $e^+e^- \to W^+W^-$ followed by one $W \to \ell + \bar{\nu}$ and the other $W \to q_1\bar{q}_2$, where ℓ is e or μ.

The analysis hence requires a standard-model Monte Carlo simulation, where one looks for an excess of events within an interval of invariant masses around some value below 175 GeV (the top mass). If such an excess is seen, the "extra events" should have a few characteristics, typical for our model, but not for the standard-model background events:

- there would be a threshold effect at the total e^+e^- energy $\sqrt{s} = M_{\nu_{\kappa 2}}$, rather than at the W^+W^- threshold.
- the charged lepton would always be back-to-back to the W (*i.e.*, the cms of the two hadron jets) in the rest system of the $\nu_{\kappa 2}$. This, in turn, has a speed given by kinematics only, *i.e.*, by $\sqrt{s}$ and $M_{\nu_{\kappa 2}}$.
- at first sight it seems as if the $\nu_{\kappa 2}$ would decay as willingly to an electron as to a muon in accordance with, *e.g.*, W decay. However, the situation is a bit more complicated, since e^- and μ^+ (not μ^-) are on equal footing in our model. They have *opposite* dominant helicity components in the ultra-relativistic limit. Although we do not know the dynamics of the heavy-neutrino decay, we suspect that its decay favours an outgoing charged lepton with positive helicity, *i.e.*, the μ^+ (and μ^- in $\bar{\nu}_{\kappa 2}$ decay). Intuitively, this seems in accordance with the helicities of the decay $W^+ \to \mu^+ + \nu_\mu$.

These predictions are best investigated by the CERN OPAL collaboration. It has so far published searches for, among others, heavy neutral leptons at $\sqrt{s}$ values up to 183 GeV [12, 13, 14]. A similar analysis at the highest LEP energies is underway [15].

The main conclusion so far from OPAL is that no signs of a heavy neutral lepton have been found at LEP energies up to 183 GeV. This result is summarised as 95% CL lower mass limits for various channels (decay modes), the values being typically around 90 GeV.

However, the OPAL analyzes contain some extra assumptions, not necessarily valid for our model. For instance, a new heavy neutrino is supposed to belong to a new "fourth family", and be produced toghether with its own antineutrino. This is not the case in our model. In the search for excited versions of the normal neutrinos it is supposed that the couplings are as prescribed by the standard model. Any differences between a normal neutrino and its excited partner is assumed to be due to the different masses only. We therefore look forward to a less model-dependent analysis of *all* available OPAL data along the directions outlined above, including the most recent ones beyond 200 GeV.

Next we consider the decay channel

$$\nu_{\kappa 2} \to e/\mu + W, \tag{11}$$

followed by

$$W \to e/\mu + \nu_e/\nu_\mu. \tag{12}$$

Now the invariant neutrino mass cannot be derived. The only signal of a new neutrino would therefore be an excess of events compared to what is expected from the standard model in the channel

$$e^+e^- \to \ell_1^+\ell_2^- + invisibles. \tag{13}$$

Here also the ALEPH collaboration can contribute to the analysis, although it focuses on W-pair production at various LEP energies [16, 17, 18, 19, 20]. This means that there are several experimental cuts in order to assure that each event produces a W-pair, which might naturally eliminate alternative processes, such as the one we are interested in.

Looking at the totality of ALEPH data, for all W decay modes, the ones taken at the lowest three LEP energies [16, 17, 18] are consistent with a small "excess" of events in some kinematic bins, but only on the 0.5σ to 1σ level. The case is weakened by the fact that other bins show similar "deficits" in comparison to Monte Carlo simulations of the standard model, hinting at a mere statistical effect. In addition, ALEPH does not find any relevant deviation from lepton universality, *e.g.*, an excess of muons, according to our speculation above that a heavy neutrino would prefer muonic decays.

At the LEP energy of 189 GeV the ALEPH statistics is much better, and the possible deviations from the standard model are even smaller, on the order of 0.2σ at the most.

The only aspect of the ALEPH data that can give some support to a closer analysis along our prediction is the fact that there is a clearer excess of events in kinematic regions outside the ("acoplanarity") cuts used to define W-pair production, especially for LEP energies up to 183 GeV. Obviously, these regions are expected to contain events with other configurations than just a W pair, but it is not clear to us why the simulations do not describe the data so well.

We now analyze the different neutrino decay mode

$$\nu_{\kappa 2} \to \nu_e/\nu_\mu + \gamma(\gamma), \tag{14}$$

or in terms of preon processes:

$$\delta(\alpha\beta) \to \beta(\alpha\delta)/\alpha(\beta\delta) + \gamma(\gamma). \tag{15}$$

Hence the full events of interest are

$$e^+e^- \to \nu\bar{\nu} + \gamma(\gamma). \tag{16}$$

The signal is one or more high-energy gammas, and a deviation in the production cross-section and the phase-space distribution of gammas, as compared to expectations from the standard model.

Such studies have been made by the DELPHI collaboration [21, 22, 23], in events with just photons (plus "invisibles"), and at LEP energies up to 189 GeV. Parts of the DELPHI analysis focus on the possibility of a new generation of heavy neutrinos.

The results are summarised as the distribution in "missing mass" of the invisibles recoiling against the gamma(s). The possible deviations of this distribution from the standard-model expectation are presented as upper production cross-section limits of a heavy "neutral object". However, this analysis is built on the idea that the heavy neutrino is "stable", and hence identical to one of the outgoing neutrinos in the process given above. Provided that its mass is fairly high, and that only high-energy gammas are studied, the "missing mass" would be a good measure of the neutrino mass. A theoretical analysis of expected event rates for such a production of a 50 GeV neutrino at LEP is presented in [26].

If we stay with the case of a highly unstable neutrino, where the gammas come from its decay (and not from its production), there is a simple relation, in the one-gamma case, between the "missing mass" (MM) of the DELPHI analysis and the mass ($M_{\kappa 2}$) of $\nu_{\kappa 2}$. Assuming that its decay products, γ and a light neutrino, are aligned along its spin direction, we get:

$$M_{\nu_{\kappa 2}} = \sqrt{E^2_{LEP} - MM^2}. \tag{17}$$

There is no such simple relation for two-gamma decays, since we do not know the dynamics behind the decay. Intuitively, it seems likely that the "missing mass" distribution would anyway peak at the same value as for the one-gamma decays, but there might also be a second peak due to the fact that the gammas can radiate in the same or in opposite directions in the $\nu_{\kappa 2}$ rest system. The only data points that deviate by more than 1σ from the standard-model result in [23] are at $MM \approx 135$ GeV in both the 2γ data and in parts of the one-gamma data (from the HPC calorimeter). This value corresponds to a $\nu_{\kappa 2}$ mass of around 140 GeV. There is also a similar excess at $MM \approx 165$ GeV in the 2γ data, possibly corresponding to a 110 GeV neutrino. However, a signal would be smeared out, since the data are summarised over several LEP energies. No significant excess is seen in the one-gamma case when the data are summed from all (three) DELPHI calorimeters.

The detailed analysis of "limits of compositeness" in [23] is not of much value for judging our ideas, because it is built entirely on predictions from a rather specific preon model [27]. These model predictions rely, for instance, on the existence of additional, composed bosons with unknown (high) masses.

Finally, one might ask if the lightest of the superheavy neutrinos, the $\nu_{\kappa 1}$, might be *stable*, and hence correspond to the hypotherical "dark-matter" neutrino analyzed in [28] and elsewhere. Since it is most probably the lightest of the superheavy particles, it can perhaps be pair-produced at LEP as $\nu_{\kappa 1}\bar{\nu}_{\kappa 1}$ (but it cannot be created together with a light partner). However, there is no particular reason for a stable $\nu_{\kappa 1}$. All superheavy leptons and quarks *must* decay through the break-up of their dipreons. Otherwise the top quark would be stable, and so would the heavy lepton κ. The $\nu_{\kappa 1}$ would indeed decay to, for instance, an e^- through the same preon processes as for $t \to b$, as can be seen in Table II.

A new, heavy quark can be studied in two different ways. One can either look for an excess of events with a high missing mass that recoils against the normal quark. Or one can try to identify the decay products of the new quark, and derive their invariant mass.

The first method should, in principle, be simpler than the second one, since it takes only to identify a c or b jet and measure its energy. Assuming that no other particles have been produced than a pair of one new and one normal quark, and that the mass of the latter can be neglected, one gets the relation

$$E_q = \frac{E_{LEP}^2 - M^2}{2E_{LEP}}, \tag{18}$$

between the mass M of the new quark and the energy E_q of the recoiling normal quark. In practice, jet energies are measured, and the relation between the initial quark energy and that of its final hadronic jet is not simple. In order to search for the h (or k), quark data are needed for jets typical for c (or b) quarks. Unfortunately, most LEP data on heavy flavours are taken at the Z^0 peak. Superheavy quarks would give broad peaks in the jet energy spectrum according to Eq. (18), on top of the background, which would most probably come from $e^+e^- \to W^+W^-$ followed by $W \to q_1\bar{q}_2$.

The second method, *i.e.*, to look for decay products of the heavy quark or lepton, is the conventional one. The two quarks h and k do not decay like the t, and cannot be discovered as a result of the search for single-top production. However, k is identical to the hypothetical fourth-generation b' quark, which has been searched for in many experiments [1]. It decays like $k \to b + x$, through $\delta(\bar{\delta}\bar{\alpha}) \to \beta(\bar{\beta}\bar{\alpha}) + x$, where x can be a γ, a Z^0 or a gluon. According to [24] the bZ^0 or cW channels should dominate the decay of a "b'", so one way to find it would be to analyze the recoiling mass against a b and a Z^0 jet, or a c and a W jet. However, their analysis is built on production of $b'\bar{b}'$ *pairs*, unlike in our model. And so is the recently published experimental search by the DELPHI collaboration [25]. We instead suggest that the analysis is remade for $b'\bar{c}$ production, which would require other kinematical cuts than in [25].

In conclusion, we argue that there might still be room for signatures of composite quarks and leptons in the CERN LEP data, provided that these are analyzed with slightly different methods in comparison to what has been done so far.

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