Opponent's report on doctoral thesis

submitted at the Charles University in Prague

Institute of Particle and Nuclear Physics

Author: **Mgr. Kateřina Sýkorová, née Jarkovská**
Thesis title: **Quantum aspects of particle physics models with extended gauge symmetries**

Study branch and programme: **Physics, Particle and Nuclear Physics**

Opponent: **Mgr. Petr Beneš, Ph.D.**
Affiliation: **Institute of Experimental and Applied Physics**
Czech Technical University in Prague
Husova 240/5, 110 00 Prague 1, Czech Republic
Phone: **+420 723 199 156**
E-mail: `petr.benes@utef.cvut.cz`

Context

Thesis contents

The thesis contains a thorough analysis of the minimal renormalizable non-supersymmetric SO(10) grand unified model at quantum level. In the first part it deals with the simplified SO(10) Higgs model. In this model the spontaneous breakdown of SO(10) down to the Standard Model (SM) gauge group $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ is achieved using scalars in $\mathbf{45} \oplus \mathbf{126}$ representation. This model is not fully realistic, as it lacks another scalar representation $\mathbf{10}_\mathbb{C}$ that is necessary to reproduce the observed fermion spectrum. Nevertheless, this simplified model is sufficient for study of the symmetry breaking patterns. Next, the second part of the thesis builds on the previous one: It considers only the most promising symmetry breaking pattern identified in the aforementioned simplified analysis, but adds the $\mathbf{10}_\mathbb{C}$ scalar representation in order to provide a (potentially) realistic model.

The author carries out the analysis consistently at 1-loop level (and in the case of gauge coupling unification even at 2-loop level). The reason is that, as shown earlier by her supervisor, only this way it is possible to avoid the tachyonic instabilities notorious in SO(10) models at tree level. In order to narrow the vast parametric space, the author defines the "viable" subspace whose elements must satisfy requirements of non-tachyonicity, gauge coupling unification and perturbativity. Subsequently, she performs numerical scans of this refined parameter space.

Last but not least, in order to make the thesis reasonably self-contained, the author provides sections giving introduction to grand unified theories in general and to the minimal SO(10) model in particular. Finally, there are several technically oriented appendices.

Main results

Analysis of the simplified SO(10) Higgs model reveals that there are only two potentially realistic patterns of the spontaneous breaking of the SO(10) down to the SM gauge group. These two symmetry breaking patterns differ by the intermediate stage symmetry group, being either $\mathrm{SU}(4)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{R}$ or $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_{\mathrm{B-L}}$. The former case is identified as strongly preferred and subsequently adopted for the analysis of the full fledged SO(10) model that, by including the $\mathbf{10}_\mathbb{C}$ scalars, allows to treat also the fermions. However, it is found that this model is unable to fit the observed fermion masses while maintaining at the same time its perturbativity.

Thesis assessment

Scientific aspects

The results presented in the thesis are by all standards relevant. Although the final conclusion itself (i.e., the inability of the minimal SO(10) model to correctly describe the Nature) is negative, it at least highlights the necessity of taking into account quantum corrections in analyses of this type of models. (This is, after all, a perfect illustration of the Weinberg's Second Law of progress on theoretical physic: "Do not trust arguments based on the lowest order of perturbation theory.")

The core of the thesis is based on two papers of which the present author is one of several co-authors (including the author's supervisor). The first paper (already published) studies the simplified SO(10) Higgs model, while the other one (at the time of writing of this report not published yet, but already submitted) analyzes the potentially realistic full SO(10) model. Accordingly, the presented results are by no means exclusively by the author herself. Therefore I appreciate that the author clearly states what are her own contributions: Calculation of 1-loop scalar masses and 1-loop beta functions for all dimensionless couplings, study of semi-analytical aspects of non-tachyonicity, analytical study of doublet fine-tuning at tree level, numerical scans of the parametric space, proper implementation of the penalization function and finally contribution to the discussion of the results.

Extent, language and formal aspects

The thesis has 116 pages, not counting the two papers included in the appendices. I consider this extent more than sufficient. The thesis is written in decent English, although using at times too long sentences that may be a bit difficult to comprehend at first reading. I noticed only a few typos. Typographically the thesis is above standard, yet some usual typographical sins have not been avoided.

Shortcomings, criticism

I'm not aware of any substantial shortcomings. There are of course some imperfections, but merely of rather formal and noncritical nature.

Just to name one: In section 1.3.1 the author *first* introduces right-handed neutrino ν_R as $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L}$ singlet and *then* she argues that its weak hypercharge Y_{ν_R} (or more precisely, its ratio to the hypercharge of the Higgs doublet) is not restricted by the anomaly freedom condition. This statement is of course true. However, the order in which the arguments are presented is a bit confusing, since already from the very introduction of the right-handed *neutrinos* (which are, by definition, electrically neutral) as weak isospin *singlets* it follows $Y_{\nu_R} = 0$.

Overall assessment of the thesis

The thesis analyzes the minimal renormalizable SO(10) grand unified theory at quantum level and comes with original and interesting results. These results were presented in two papers, at least one of which has already been published. The present author is one of several co-authors of these papers, yet she contributed significantly to the results. Besides presenting new results, the thesis also meets the formal criteria, is readable and, last but not least, can serve as an introduction into the realm of SO(10) models for a newcomer.

The author demonstrated that she has mastered the field, is competent enough to devise new results and that she can communicate these results in a clear way. In other words, she proved that she is fully qualified for independent scientific work.

Questions to be asked/answered at the waiver

- Just to make it clear if this is only a typo or if I overlooked something: The first two lines in table E.1 seem to be in contradiction with equations (2.46) and (2.47). Perhaps the symbols $M_S^2(1,3,0)$ and $M_S^2(8,1,0)$ in E.1 are just swapped?
- The tachyonic problem could be, in principle, solved also by setting $a_2 = 0$. Why is this scenario not considered? Is it because the resulting Nambu–Goldstone bosons would be, due to their exact masslessness, phenomenologically unacceptable? Or is there another reason?
- The tree-level masses of tachyonic states $(8,1,0)$, $(1,3,0)$ and, presumably, also $(1,1,0)$ vanish not only when $a_2 = 0$, but also when $\omega_{BL} = \omega_R$, as can be seen from equations (2.46), (2.47) and (2.49). Is it just a coincidence, or does it also correspond to the spontaneous breakdown of some accidental global symmetry?
- How to interpret the negative result regarding the physical viability of the minimal SO(10) model? Perhaps some next-to-minimal SO(10) model would do better? Or should one abandon the SO(10) group altogether and resort to models based on another gauge group?

Résumé

(Overall pass/fail as a doctoral thesis)

I do recommend the thesis to pass as a doctoral thesis.

Date, place, name and signature of the opponent:

Prague, August 21, 2023 Petr Beneš