Reviewer's Report on the PhD thesis

Tomáš Brauner:

Spontaneous symmetry breaking in strong and electroweak interactions

Topics of the dissertation

Symmetry principles play a vital role in our description of the laws of Nature. However, symmetries are seldom exact and more often approximate; when formulating and solving a physical theory it is equally important to identify the underlying symmetry as to understand whether (and how) the symmetry breaks, and physical consequences of symmetry breaking.

The thesis deals with symmetry breaking in the theories of strong and electroweak interactions. These theories constitute a basis for the standard model of elementary-particle interactions. However, in spite of a huge amount of work invested into investigations of the standard model in the last more than thirty years, a part of problems remains unsolved, including some related to the breaking of symmetries of strong and electroweak interactions. Some of them are addressed in Tomáš Brauner's thesis. It is therefore beyond question that the problems of the thesis were well-chosen, are very relevant and particularly topical.

Remarks on the structure and contents of the dissertation

The thesis is a commented collection of reprints of scientific papers of its author, and as such consists of two parts. The first part comprises six chapters, the list of author's related publications (altogether 9 items), and the bibliography. The rest of the thesis contains reprints of 4 papers by the author (two of them with coauthors) published in prominent scientific journals.

The first two chapters of the thesis present a brief introduction to spontaneous symmetry breaking in physical theories. The author explains both the Wigner–Weyl and Nambu–Goldstone realizations of symmetry and the essence of the Goldstone theorem. General ideas and statements are then exemplified on the Heisenberg ferromagnet. Then he discusses two physical models with spontaneous symmetry breaking, the linear sigma model and the Nambu–Jona-Lasinio model, the former as a prototype of theories in which the symmetry is broken by a non-zero vacuum expectation value of an elementary scalar field, the latter being an example in which a composite operator develops a v.e.v. Both models are relevant for further parts of the thesis.

The next three chapters contain original results of the thesis (which I will comment below). The last chapter summarizes conclusions. It also critically assesses some shortcomings and simplifying assumptions of the presented results, and improvements which are currently being pursued by the author.

The structure of the thesis – reprints with commentaries – might cause an inconvenience for the reader by forcing her/him to jump between the main text and the reprints very often. However, Tomáš Brauner managed to overcome the danger successfully. The first half summarizes main results in a self-contained way without details. Only the reader interested in technicalities and detailed information has to read the appended reprints.

Still, there are a couple of places where the author might have been less laconic. In Chapter 2, on page 6, he stated that he would be concerned with spontaneously broken *continuous internal* symmetries. More precisely he should have added the adjective *global*. In a similar way, on page 14, when stating that *"there is no spontaneous symmetry breaking in finite volume"*, *global* would again be in place; the local symmetry cannot break spontaneously (without gauge fixing) even in the infinite volume. In this context, the author might have referenced the important Elitzur's theorem[1]. In Section 2.3.2 the author introduces the Nambu–Jona-Lasinio model and operates with expressions like (2.11) without explicitly mentioning that the integral contained is divergent and needs to be regulated by a cut-off (and the model itself is non-renormalizable).

However, all my comments are just minor points. The thesis as a whole is written in a concise, yet unusually clear way, and proves author's deep insight into its topics. I would also like to mention a nontrivial point: the author's advanced command of the English language and style, which is not at all commonplace in physics PhD theses, at least in the Czech and Slovak context.

Results

Original results of the paper are contained in chapters 3–5. Chapter 3 discusses a general question of how many Goldstone bosons are associated with a given pattern of symmetry breaking. It is shown, in variants of the linear sigma model with non-zero chemical potential, that there exist Goldstone bosons with a quadratic dispersion relation, and that their appearance is related to nonzero density of Noether charges. I have just a comment: The title of this chapter (*Goldstone boson counting in nonrelativistic systems*) seems a bit misleading to me. It is true that the "abnormal" number of Goldstone bosons appears in nonrelativistic systems, but more generally in *Lorenz-noninvariant* ones, and the author in fact studies a particular type of these, *relativistic* theories with non-zero chemical potential.

Chapter 4 introduces a novel mechanism of dynamical breakdown of electroweak symmetry (and generation of fermion masses) by a strong Yukawa interaction of massless fermions with massive complex scalar fields. How the mechanism operates is illustrated on a toy Abelian model, the extension to non-Abelian electroweak symmetry seems, at least at the first sight, straightforward, but has not yet been completely worked out.

Finally, Chapter 5 studies the theory of strong interactions, QCD, at finite baryon densities, and investigates the effect of color superconductivity as a consequence of the unconventional color-sextet condensate at moderate density. In the second part of this chapter, the author constructs chiral perturbation theory for a QCD-like theory – its two-flavor, two-color variant – at finite chemical potential.

The reviewer is expected to assess the importance of the results of the thesis. This task has been made easy for me by anonymous referees of Brauner's papers, and I find no reason to question their competence. The papers were published in prominent scientific journals with high impact factors (Physical Review D in particular), and that is sufficient evidence for me that the results of the thesis are sound and relevant. What I would only like to stress is the breadth of the author's interests, covering effects of symmetry breaking in general, as well as particular realizations in electroweak- and strong-interaction theories. In the case of the electroweak theory, one of the most prominent and longstanding problems of the standard model is attacked in this thesis in an ambitious way. If the proposed model turned out to be close to the truth, this would represent a major breakthrough in the field and earn deserved fame to the author and his supervisor.

My only reservation with respect to the results of the thesis is that they were obtained from tree-level Lagrangians, or with simplifications omitting most quantum corrections. It will be important to at least estimate their effects. However, it is fair to say that the author is aware of this shortcoming and working on improvements (see the discussion in the concluding chapter).

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[1] S. Elitzur, *Impossibility of spontaneously breaking local symmetries*, Phys. Rev. D 12, 3978-3982 (1975).

Questions to be addressed during the thesis defence

As I said above, the thesis is very well and clearly written, and I have no "wicked" questions to the author to address during the defence. For the sake of scientific discussion, I would like to ask him for his opinion on the following questions:

1. For critical Yukawa couplings of fermions to massive scalars in the Abelian variant of the model of dynamical symmetry breaking, the author quotes one value in the paper ($y_{crit} \approx 35$, Sec. V of the reprint [II]), another in the main text (about 30, on page 36), and yet another (much larger) in the footnote on the same page. Does this mean that the dependence on y is rather weak? What is your current "official" value, after all errors were eliminated? How strongly do dynamically generated fermion masses depend on the Yukawa couplings?

2. In the realistic case, parameters of the proposed model of dynamical electroweak symmetry breaking have to meet some constraints not to contradict the existing experimental data. Can you give an estimate e.g. how large would the masses of scalar particles have to be? Are they in reach of future experiments at the LHC?

3. If the answer to the last question is affirmative, how could one distinguish "your" scalars from the ordinary Higgs scalar of the standard model? What might be the signatures?

Conclusion

In my opinion, the thesis of Tomáš Brauner meets the highest standards, proves him to be a bright, talented, inventive physicist with broad interests, ready to undertake independent research. After he successfully defends the thesis, **I strongly recommend to confer on Tomáš Brauner the academic degree of *Philosophiae Doctor* (PhD).**

Bratislava, May 3, 2006.

[redacted]

Bratislava.