Referee's report on the thesis titled **New Dynamics for Canonical Loop Quantum Gravity** submitted by **Mr. Mehdi Assanioussi** for the degree of Doctor of Philosophy and supervised by Prof. dr hab. Jerzy Lewandowski.

The main goal of the thesis is to study the dynamics of Loop Quantum Gravity (LQG), arguably, the most important remaining point that needs to be solved to allow us to claim that LQG is a viable theory of quantized general relativity. I would like to highlight, already at this point, the fact that the work presented by Mr. Assanioussi deals with this very hard and central problem. The author has taken certain risks by choosing this subject for his thesis but, in my opinion the result is very good. The thesis is well written, the methods that he uses are carefully explained as well as the motivation of the work and the conclusions. The results discussed in the thesis have provided the material for a number of research papers co-authored by Mr. Assanioussi and published in Physical Review D. As far as I can see **the thesis meets all the criteria that a doctoral thesis should satisfy**. I would like also to explicitly state that, in my opinion, **it deserves to be nominated as outstanding**.

In the following I will support my evaluation with a review of the points that, in my opinion, are indicative of the quality of the work presented in the thesis.

The problem

Loop Quantum Gravity was proposed thirty years ago as a new way to approach the quantization of general relativity within the so called canonical framework. The shift from the standard geometrodynamical variables to a new set of geometric objects (the Ashtekar variables, related to the ones used in Yang-Mills theories), provided a completely different setting that has led to enormous progress in quantum gravity. At the present moment we have at our disposal a rigorous mathematical setting where the relevant questions can be asked, many of them have been answered, and the solution to most of the remaining problems can already be glimpsed. The picture of space-time that arises is very rich and, certainly, very different from the old ones.

In my opinion, the most important problem that has to be solved to render LQG *the* theory of quantum gravity is the successful implementation of a mathematically consistent, physically viable and usable quantum Hamiltonian constraint. Only then we will be able to understand the quantum dynamics of general relativity and approach the hopefully very rich phenomenology of quantum gravity. I would like to mention at this point that other important issues —among them the off-shell quantum algebra of constraints and the crucial understanding of the semiclassical limit— can only be understood once the problem of the Hamiltonian constraint is solved. Of course there has been plenty of work on this particular problem by many researchers —and important technical advances— but the final success is proving to be quite elusive. Some of the ideas developed in the thesis provide interesting new avenues to finding the sought for Quantum Hamiltonian operator. In my opinion one of the strong points of the thesis is the enormous relevance of its subject matter.

The structure of the thesis: methodology

After the introduction, the second chapter of the thesis is a very readable and to the point discussion of the methods used in LQG. I like, in particular, the very nice discussion of the older approaches —originating in Thiemann's work— to the definition and implementation

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of the Hamiltonian constraint and the technical problems of those constructions. This is necessary background for the main subject of the thesis.

Chapters III and IV contain the main results of the thesis. Chapter III is devoted to the introduction of alternative dynamics in vacuum LQG. In order to avoid the technical problem posed by the fact that the "old" quantum scalar constraint does not preserve the Hilbert state of diff-invariant states, a new vertex Hilbert space $\mathcal{H}^G_{\rm vtx}$ has been introduced by Lewandowski and Sahlmann. In this Hilbert space it is possible to implement in a nice way a variant of the usual Hamiltonian constraint in LQG consisting of the standard EEF term plus an additional scalar curvature term (with a pre-factor containing the Immirzi parameter). The main advantage of the curvature term is the possibility of borrowing Regge calculus methods to construct a quantum curvature operator. The properties of this operator, including its spectrum, are carefully discussed in this chapter. The other piece of the scalar constraint (referred to by the author as the Euclidean operator) can also be defined in $\mathcal{H}^G_{\rm vtx}$ and regularized by using special loops. With these two pieces it is possible to write a symmetric and densely defined operator in $\mathcal{H}^G_{\rm vtx}$. This operator is Diff-covaraint and anomaly-free but it remains to be seen if it is self-adjoint. The construction of physical states (by averaging) and the discussion of the quantum constraint algebra are also briefly discussed in this chapter.

The very interesting chapter IV discusses a new approach to the introduction of dynamics in LQG by using *deparametrization.* Two particular models are studied in detail. In the first gravity is minimally coupled to a massless scalar field and in the second to a dust reference field. Deparametrization is achieved by eliminating the scalar field and its canonical momentum (resp. dust) from the set of phase space variables by using the constraints. By doing this it is possible to write non-zero Hamiltonians involving only the gravitational variables and consider their quantization. In these examples the physical Hilbert space is the space of $SU(2)$ and Diff-invariant states with the scalar product inherited from that of the kinematical Hilbert space. The regularization procedure for the two quantum Hamiltonians is carefully discussed also in this chapter.

The final part of chapter IV contains an interesting proposal to deal with the Hamiltonian operators previously introduced in the chapter. The key idea is to use the Immirzi parameter to perform perturbation expansions (in the spirit of the standard time-independent perturbation theory of quantum mechanics) by considering the Euclidean part as a perturbation of the Lorentzian part. It is interesting to mention here that the Immirzi parameter appears in the Holst action as a coupling constant of sorts, so this perturbative approach is quite natural. The proposed method is used to perform a numerical analysis of the evolution of the geometric operators representing the volume and the curvature in the two deparametrized models.

The thesis ends in chapter V with a summary of the main results and suggestions for improving the models discussed in the thesis.

The main results

The main results of the thesis are the following:

- The construction of a quantum scalar constraint that preserves the Hilbert space $\mathcal{H}^G_{\rm vtx}$ of partially diff-invariant states. This operator can be used to obtain symmetric scalar operators that may be self-adjoint.

- The use of the regularization procedure introduced in the construction of the scalar constraint operator just mentioned to define two different quantum Hamiltonians for deparametrized models (gravity plus scalar field and gravity plus irrotational dust).
- The use of time-idependent perturbation theory to study the dynamics of these models.
- The numerical study of the quantum evolution of some observables defined by the two Hamiltonian operators defined in the thesis.
- The rigorous construction of a curvature operator (an interesting addition to the family of geometric operators already defined in LQG).

Closing remarks

As I have already mentioned above the quality of the thesis is very high. It is very well structured and written, the main ideas are carefully explained, and the methods used are sound. It is clear that the author masters the complex tools used in the work and has a very solid background in LQG. If his defense is good I believe that he deserves the maximum grade.

J. F. de B. G.