infinities would be a good way to discover correct physical laws, and I was wrong. I've often been wrong in guessing the best way to proceed." (Feynman, 1989, p. 199.)

1.5. Quantum Field Theory in Curved Spacetime

The first attempt at formulating quantum field theory in a curved spacetime can be traced to Schrödinger (1939), but a canonical scheme for the second-quantization of fields in curved spacetime was first systematically studied by L. E. Parker (1968, 1971). Since that time this subject grew to the extent that it became the topic of monographs (cf., e.g., Birrell and Davies, 1982; Fulling, 1989) and entire conferences (cf., e.g., Audretsch and de Sabbata, 1990), despite the fact that, as pointed out in one of these monographs: "*There does not exist a quantum field theory formalism in an arbitrary curved spacetime*. This problem is deep-rooted and arises from the fact that standard formalisms of field theory require a preferential slicing in spacetime." (Narlikar and Padmanabhan, 1986, p. 277.)

More specifically, the review article "Quantum Field Theory in Curved Spacetime" by B. S. DeWitt (1975) lists, in a section entitled "Failure of conventional procedures," the following difficulties:

"This [canonical quantization procedure of fields in curved spacetime] is just as in conventional particle physics. The trouble with it is: *it's wrong*. It is not wrong in a technical mathematical sense. It simply provides a grossly inadequate foundation for the theory. Here are just some of the situations where it fails:

1. There may be no Killing vector at all, timelike or spacelike. This is the generic situation. How to deal with it is unknown, except possibly when there is an approximate Killing vector that becomes exact asymptotically. ...

2. There may be a global Killing vector, but it may not be everywhere timelike. ...

3. Spacetime may be stationary only in limited regions. If each region possesses complete Cauchy hypersurfaces then a local timelike Killing vector field may be set up in each and vacuum defined for each [such region]. ... " (DeWitt, 1975, p. 302).

However, even in those cases where there is a global timelike Killing vector field, so that the Lorentzian spacetime manifold is stationary but not static, foundational difficulties remain, since the prediction of conventional QFT in such curved spacetimes is that *inertial* detectors will register spontaneous pair creation *ex nihilo* .

This phenomenon is usually compared (Birrell and Davies, 1982) with some of the results obtained when the canonical quantization of fields in Minkowski space is *formally* carried out in Rindler coordinates, rather than in the Minkowski coordinates used by Dirac (1927) in founding QFT. Indeed, such a purely formal adaptation of the canonical second-quantization scheme then leads to spontaneous pair creation *ex nihilo* that is not part of the energy-conserving and well established phenomenon of pair creation for quantum fields in Minkowski space, but rather "suggests a rather surprising viewpoint of this [spontaneous Rindler] radiation: it seems as though the detector is excited by swallowing part of the vacuum fluctuation of the field in the region of spacetime containing the detector. This liberates the correlated fluctuations in a noncausally related region of [Minkowski] spacetime to become a real particle." (Unruh and Wald, 1984, p. 1055)

Thus, according to this type of analysis, in Minkowski spacetime "a uniformly accelerated observer will "see" thermal radiation (Davies, 1975; Unruh, 1976) even though the field is in a vacuum state and, as far as inertial observers are concerned, no particles are detected whatever." (Birrell and Davies, 1982, p. 54.) On the other hand, it is conceded that, possibly, "basing one's treatment of these [pair creation *ex nihilo*] concepts on the considerations of accelerated observers is a fraud, because inertial observers occupy a special status in most physical theory." (*ibid.*, p. 55.)

Indeed, ever since the inception of classical mechanics by Newton, inertial frames have enjoyed a special status in physics. In particular, the laws set by Newton were presumed to hold true *only* in inertial frames, with *fictitious* forces (such as Coriolis forces, centrifugal forces, etc.) making their appearance only if a transition to accelerated frames were performed. This special status of inertial frames and inertial observers has been retained in special relativity – and in fact it has been implicitly transferred by Einstein also to general relativity (cf. Friedmann, 1983, Chapter V). Thus, the physical and conceptual problems encountered by conventional QFT in curved spacetime have roots that run all the way into the foundations of general relativity. They, therefore, deserve special attention, and the remainder of this section will be devoted to them.

The contention that *ex nihilo* particle production is an observer dependent phenomenon raises the question whether "observers" can transcend into "creators." In particular, the point of view that "Rindler particles," as well as all the other "particles" allegedly observable *only* by select classes of noninertial observers in Minkowski spacetime, actually exist, has to contend also with the following fundamental epistemological difficulty: if *something* is presumed to be literally created out of what is *physically* nothing, what is there to prevent the creation in this manner of *any* kind of object? In other words, what is there to prevent the creation of Rindler particles of *any* mass, spin, charge, etc.?

Despite its obvious nature, this question does not appear to have been raised and discussed in the literature. This might be because the Fock vacuum of such models is mentally identified with the "dressed vacuum" of quantum field theories for interacting fields which, on account of the customary renormalization procedures, is inhabited by an infinity of "bare" particles. However, the above arguments concerning Rindler particles apply to *free* quantum fields in Minkowski space, so that the "dressed vacuum" of quantum field theories for interacting fields has no bearing on them. Consequently, even if some form of *apparently* spontaneous particle production were observed in high-energy particle accelerators, that still would not represent a true test for the existence of Rindler particles.

Indeed, the hallmark of such a "particle" is not only its violation of *local* energy conservation, reflected by the prediction that it "liberates the correlated fluctuations in a noncausally related region of [Minkowski] spacetime to become a real particle" (Unruh and Wald, 1984, p. 1055), but also the *indiscriminate nature of Rindler particle production*, whereby each species of particle has an equal chance of being produced literally out of a vacuum, rather than as a result of an energy-conserving collision process. As a corollary of these manifestations, it might even appear that a Rindler perpetuum mobile could be created, whereby unlimited amounts of energy could be produced by the simple expedient of accelerating any material object, of however small rest mass, to sufficiently high acceleration in relation to any inertial frame – such as a (terrestrial) laboratory frame.

The only way out of this ultimate paradox is to suggest that in a particle accelerator the energy for producing the Rindler particles, which an accelerated micro-detector would register, might come from the accelerator itself, since as it accelerates the micro-detector, "the work done by [it] ... supplies the missing energy that feeds into the [quantum] field via the quanta emitted from the detector." (Birrell and Davies, 1982, p. 55.) But in that case the whole Rindler particle production phenomenon is due to the fact that an open system, capable of receiving energy from the outside (i.e., from the accelerator), was treated as a closed system – whereas the physically *correct* treatment should have incorporated from the outset all the quantum fields created by the accelerator during the acceleration process. In that case the same argument cannot be applied to a similar micro-detector in *free* fall[4], despite all the manifest formal analogies between Rindler particle production and the particle creation *ex nihilo*, which are very much stressed in some of the literature on the subject. Indeed, if the strong equivalence principle of general relativity is correct, then *"observers" in free fall are truly inertial* – and as such they are not to be viewed as being accelerated by an external gravitational field, as is the case in Newtonian mechanics.

On the other hand, if it is assumed that a freely falling observer in curved spacetime is, contrary to Einstein's point of view, an accelerated observer, the question arises: in relation to what is he accelerated? The only *mathematical* answer to that question that can be found in the literature is that, in the case of curved spacetimes that are *asymptotically* flat, an observer in free fall is accelerated in relation to an observer in the *fictional* flat spacetime that asymptotically merges with the considered curved spacetime. However, since no acceptable cosmological models of our universe as a whole are asymptotically flat, even such an *ad hoc* "solution" does not provide a truly satisfactory answer.

These fundamental difficulties of the conventional framework for quantum fields in curved spacetime extend also to its formulation of the vacuum state. Indeed, it is again acknowledged in standard literature on the subject that "as far as Minkowski space is concerned, the [Fock] vacuum is a strong candidate for the 'correct' or 'physical' vacuum – the experiences of the accelerated observers being 'distorted' by the effects of their non-uniform motion. The trouble is that when gravitational fields are present, inertial observers become free-falling observers, and in general no two free-falling detectors will agree on a choice of vacuum." (Birrell and Davies, 1982, p. 55.)

We can infer from all this that the above mentioned "lack of agreement" between various free-falling detectors is due to the fact that in CGR all inertial observers are *local* observers, whereas the only "vacuum" considered in conventional quantum fields in curved spacetime is a *global* vacuum. Hence, as part of the solution to all of the above fundamental inconsistencies, we shall offer from Chapter 5 onwards a quantum geometry framework for QFT based on fibre bundles whose fibres are Fock spaces, so that *all* Fock vacuum states will be local rather than global.

1.6. From Canonical Quantum Gravity to Superstrings

The opinion that Einstein's theory of gravity has to be quantized is very widely held, but there are exceptions: Møller (1952) and Rosenfeld (1957) have argued that the gravitational

---

[4] Cf. Sec. 2.6 for a discussion of the geodesic postulate and of the strong equivalence principle governing all free-fall conditions in CGR.