6. The Time Arrow in Quantum Cosmology

The founders of quantum theory invented their theory as a theory of atoms, that was soon successfully applied also to other microscopic systems. Macroscopic objects were thought to require the established classical concepts. This point of view still seems to form the majority opinion among physicists in spite of their assertion that quantum theory be universally valid. We have seen in Sect. 4.3 that this schizophrenic position is not inevitable, since decoherence allows quasi-classical concepts to emerge from quantum mechanical ones within reasonable assumptions.

Everett (1957) seems to have first seriously considered a wave function of the universe (that must contain internal observers, required for its interpretation). Although he had in mind the quantization of general relativity with its cosmological aspects, Everett applied his ideas, which were based on a time-dependent Schrödinger equation, to nonrelativistic quantum theory. His main interpretational obstacle was the entanglement arising from measurements described by means of von Neumann’s unitary interaction (4.30). This led him to his ‘extravagant’ interpretation (in Bell’s words) in terms of many quasi-classical ‘branches’, which are separately experienced but are all assumed to exist in one superposition that defines the true and dynamically consistent quantum world. Beyond measurements proper and occasional interactions he does not seem to have regarded entanglement as particularly important (cf. Tegmark 1998).

The quantitative considerations reviewed in Sect. 4.3 have shown that uncontrollable (‘measurement-like’) interactions with the environment are essential and unavoidable for almost all systems under all realistic circumstances. Strong entanglement is, therefore, a generic aspect of quantum theory. The more macroscopic a system, the stronger its entanglement with its environment. The concept of a (pure) quantum state can be consistently applied only to the universe as a whole (Zeh 1970, Gell-Mann and Hartle 1990). This seems to be a far more powerful argument for quantum cosmology than merely an attempt to quantize general relativity or some unified field theory.

The quantum state of the universe must then also include quantum gravity (entangled with matter) with its novel conceptual consequences (see Sect. 6.2). However, many quantum cosmological aspects may be formulated on a quasi-classical background spacetime, using a fixed foliation, parametrized by a time coordinate $t$. Global states can then be dynamically described.
by means of a time-dependent Schrödinger equation with respect to this co-
ordinate time $t$. This dynamics will be derived from quantum gravity (with
its concept of an intrinsic time) in Sect. 6.2.2 as an approximation. Global
states (such as those of quantum fields) depend on a foliation (or a reference
frame) even on flat spacetime, while the density matrix of any local system
should be invariant under a change of foliation that preserves the local rest
frame – a requirement that does not seem to have attracted much attention.

If the quantum universe is thus conceptually regarded as a whole, it
does not decohere, since there is no environment. Decoherence is meaningful
only for subsystems of the universe, and with respect to observations by other
subsystems (Wheeler's 'observer-participators'). If, furthermore, no objective
collapse of the wave function is assumed to apply, one is forced to accept
Everett's 'extravagant' wave function, which is a superposition of all 'possible'
outcomes of measurements and measurement-like processes that ever occoured
in the universe. This global quantum state may always be assumed to be pure,
since a global density matrix could be consistently interpreted as representing
incomplete information about such a pure state. A measurement that merely
selects a subset from those states which diagonalize this density matrix would
be equivalent to a classical measurement (as depicted in Fig. 3.5 – in contrast
to Fig. 4.3).

Initial and (nontrivial) final density matrices for the universe were sug-
gested by Gell-Mann and Hartle (1994) to be used in Griffith's expression for
probabilities of 'consistent histories'. Applied to individual measurements (cf.
Sect. 4.6), final conditions would describe postselection, as discussed by Ahar-
aronov and Vaidman (1991) – see also Vaidman (1997). In contrast to Everett
or collapse models, these interpretations do not assume the wave function
itself to characterize reality, but leave something else to be selected.

The decoherence of subsystems according to a global Schrödinger equa-
tion leads dynamically to robust branches. These branches form dynamically
autonomous components of the global wave function that may factorize in the
form $\psi_{\text{obs}1}\psi_{\text{obs}2} \ldots \psi_{\text{rest}}$ with respect to 'observer states' describing robust
(objectivizable) memory (cf. Sect. 4.3.2 and Tegmark 2000). This specific uni-
tary evolution requires a fact-like arrow of time corresponding to a cosmic
initial condition of type (4.56). Branching into components which contain
definite observer states has to be taken into account in any effective dyna-
mics that is to describe the history of the (quasi-classical) 'observed world' in
quantum mechanical terms (cf. Fig. 4.3). It need not represent an objective
(albeit objectivizable) fundamental dynamical process. The decrease of phys-
ical entropy, characterizing this 'apparent collapse' into a specific outcome,
may be negligible on a thermodynamical scale in the usual situation of a
measurement. Yet it may have dramatic consequences for phase transitions
which describe a dynamical symmetry-breaking of the global vacuum. This
will now be discussed: