This apparent ensemble of discrete numbers is dynamically approximately described by a master equation. Therefore, it is formally equivalent to an ensemble of solutions of a stochastic (Langevin-type) equation that essentially describes individual discrete 'histories' $n(t)$ – here in the form of 'descending staircase functions'. In terms of a universal Schrödinger equation, the number of undecayed nuclei $n$ is a 'robust' property in the sense of Sect. 4.3.2 if decay can be assumed to be irreversible (in particular when monitored by detectors). The various dynamically robust branches of the wave function, arising by the fast but smooth action of decoherence, describe individual histories for integer numbers $n(t)$, which represent successions of almost discrete quantum jumps at certain times $t_1, t_2, \ldots$ (as discussed in Sect. 4.3.6). Similar staircase functions have now also been observed for decaying photons in a cavity (Gleyzes et al. 2006) – thus directly confirming Fig. 3.30 of Joos et al. (2003). However, deviations from exact steps can always be calculated if the interaction with the environment is known (Joos 1984): quantum theory is *not* a stochastic theory for quantum jumps.

## 4.6 The Time Arrow in Various Interpretations of Quantum Theory

> The truth could not be worth much
> if everybody was a bit right.

Physicists who completely agree about all applications of quantum mechanics often differ entirely about its interpretation, and even on the question of whether there remain *any* meaningful problems beyond the mere formalism (see Fuchs and Peres 2000). Although most of them would agree that quantum theory allows no more than probabilistic predictions, they often *derive* irreversible master equations, which describe an increase in entropy, from the deterministic and time-symmetric Schrödinger equation, using special initial conditions as in classical statistical physics (see Sect. 4.1.2). However, a dynamical probability interpretation must be relevant for the arrow of time – regardless of whether it is based on a fundamental stochastic (time-asymmetric) law or on an incompleteness of the theory (hidden variables) that refers to an unknown future. Its consequences cannot be avoided just by adding new words. For example, quantum theory is often called 'deterministic but acausal' – while this statement is then justified by the 'uncertainty' of classical properties (such as particle positions or momenta), which just *do not apply* to quantum states. Most physicists seem to disregard this consistency problem in an act of *Verdrängung*.

The deepest roots of these conceptual inconsistencies seem to arise from the fundamental difference between Heisenberg's and Schrödinger's 'pictures' (see Zeh 2004). While Heisenberg maintained classical concepts in principle (suggesting only a limitation of the 'certainty' of their values), Schrödinger described microscopic physical states by wave functions, which can be regarded as certain. The classical configuration space on which they are usually defined would thereby replace three-dimensional space as a new 'arena of dynamics' rather than describing *potential states*.[6] Whether wave functions or 'observables' (which *formally* replace the classical variables in the Heisenberg picture) carry the dynamical time-dependence is merely a *consequence* of the chosen picture.[7]

Although both pictures are equivalent when used to calculate formal expectation values for isolated systems, they describe the time arrow of quantum measurements in different ways. Most physicists seem to subscribe to one or the other picture (or perhaps a variant thereof) when it comes to interpretations ('probabilities for *what*?'). Typically, in the Schrödinger picture one regards the collapse of the wave function as a dynamical process, while in the Heisenberg picture it is viewed as an (extraphysical) increase of 'human knowledge'. I hope that keeping this difference in mind for the rest of this section may help to avoid some misunderstandings that often lead to emotional debate. One should therefore concentrate on what is actually *done* when the theory is successfully applied – though not in a merely pragmatic way. Which concepts are *fundamentally required*, rather than being approximately justified, or even mere tradition and prejudice?

Any meaningful concept of incomplete information or knowledge has to refer to an *ensemble* of possible states. For example, physical entropy, which quantifies irreversibility, is in quantum statistical mechanics defined by means of von Neumann's functional of the density matrix (4.4). According to Sect. 4.2, it measures the size of (genuine or apparent) ensembles of mutually orthogonal (hence operationally distinguishable) *wave functions*. While only *genuine* ensembles represent incomplete information, the time-dependence of the density matrix determines that of local entropy in general. Conservation of *global* von Neumann entropy reflects the unitarity of the von Neumann equation (when applicable) – equivalent to the unitarity *and* determinism of the Schrödinger equation. No ensemble of classical or any other (unknown)

[6] The identity of configuration space and space in single particle quantum mechanics is a consequence of the exceptional kinematics of mass points. This has led to a popular confusion of single-particle wave functions with spatial fields, and to the misnomer of a 'second quantization' in quantum field theory – see Zeh (2003).

[7] This contrast between the Heisenberg and the Schrödinger pictures has to be distinguished from the 'dualism' between two competing classical concepts (particles and fields) that is part of *one* (the Copenhagen) interpretation. In classical theory, particle positions and field strengths characterize *different physical objects*, which are both constituents of general physical systems. A dualism (or 'complementarity'), apparently required to characterize quantum objects, should more correctly be understood as a conceptual inconsistency, often attributed to a 'lacking microscopic reality'. However, this conceptual dualism applies only to the 'phenomenological reality' (see Sect. 4.3.2). A critical account of the origin of these conceptual problems can be found in Beller (1996, 1999).

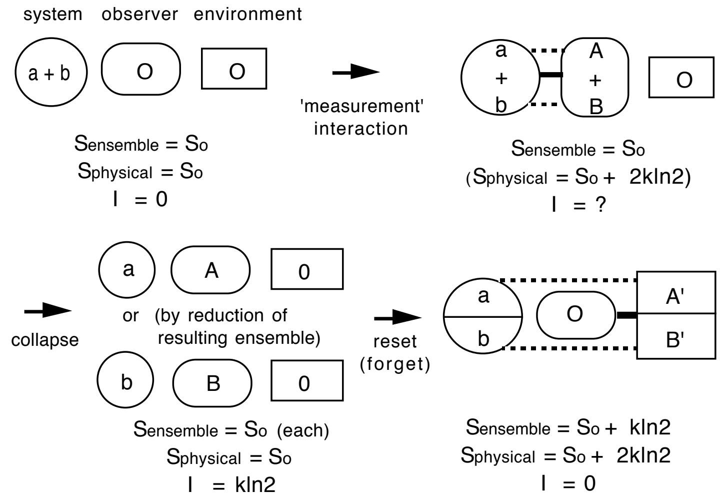


**Fig. 4.3.** Quantum measurement of a *superposition* $(|a\rangle + |b\rangle)/\sqrt{2}$ by means of a *collapse* process, here assumed to be triggered by the macroscopic pointer position. The initial entropy $S_0$ is smaller by one bit than in Fig. 3.5 (and may in principle vanish), since there is no initial ensemble '*a or b*' for the property to be measured. Dashed lines before the collapse now represent quantum entanglement. (Compare the ensemble entropies with those of Fig. 3.5!) The collapse itself is often divided into two steps – see (4.54) below: first increasing the ensemble entropy by replacing the superposition by an ensemble, and then lowering it by reducing the ensemble (applying the 'or' – for macroscopic pointers only). The total increase of ensemble entropy, evident in the final diagram, is a consequence of the first step of the collapse. It brings the entropy up to its classical initial value of Fig. 3.5. The reset here illustrates also why decoherence is usually irreversible even when a measurement result is 'erased' (and even without a collapse – in which case the final ensemble entropy would again be $S_0$). From Chap. 2 of Joos et al. (2003)

variables representing the potential values of observables is 'counted' by von Neumann's entropy. Figure 3.5, characterizing classical measurements, *cannot* therefore be applied to quantum measurements. In terms of quantum states it has to be replaced by Fig. 4.3, which includes a collapse of the wave function. The transition from a superposition to an ensemble (depicted by the second step) affects the final value of von Neumann's 'ensemble' entropy (that would be reduced by a mere increase of information, as in the first step of Fig. 3.5). For similar reasons there can be no 'postselection' (no retarded increase of information about the past) by a quantum measurement, as suggested by Aharonov and Vaidman (1991): there is nothing to 'select' from in the absence of an ensemble of hidden variables.

A wave function *and* a set of classical configurations are kinematically used in Bohm's quantum theory (Bohm 1952, Bohm and Hiley 1993). This theory is often praised for exactly reproducing all predictions of conventional