4 Nerve Terminals and the Need to Use Quantum Theory

Many neuroscientists who study the relationship of consciousness to brain processes want to believe that classical physics will provide an adequate rational foundation for that task. But classical physics has bottom-up causation, and the direct rational basis for the claim that classical physics is applicable to the full workings of the brain rests on the basic presumption that it is applicable at the microscopic level. However, empirical evidence about what is actually happening at the trillions of synapses on the billions of neurons in a conscious brain is virtually nonexistent, and, according to the uncertainty principle, empirical evidence is *in principle* unable to justify the claim that deterministic behavior actually holds in the brain at the microscopic (ionic) scale. Thus the claim that classical determinism holds in living brains is empirically indefensible: sufficient evidence neither does, nor can in principle, exist.

Whether the classical approximation is applicable to macroscopic brain dynamics can, therefore, only be determined by examining the details of the physical situation within the framework of the more general quantum theory, to see, from a rational perspective, to what extent use of the classical approximation can be theoretically justified. The technical questions are: How important *quantitatively* are the effects of the uncertainty principle at the microscopic (ionic) level; and if they are important at the microscopic level, then why can this microscopic indeterminacy never propagate up to the macro-level?

Classical physical theory is adequate, in principle, precisely to the extent that the smear of potentialities generated at the microscopic level by the uncertainty principle leads via the purely physically described aspects of quantum dynamics to a macroscopic brain state that is essentially one single classically describable state, rather than a cloud of such states representing a set of *alternative* possible conscious experiences. In this latter case the quantum mechanical state of the brain needs to be *reduced*, somehow, to the state corresponding to the experienced phenomenal reality.

To answer the physics question of the extent of the micro-level uncertainties we turn first to an examination of the quantum dynamics of nerve terminals.

4.1 Nerve Terminals

Nerve terminals lie at the junctions between two neurons, and mediate the functional connection between them. Neuroscientists have developed, on the basis of empirical data, fairly detailed classical models of how these important parts of the brain work. According to the classical picture, each 'firing' of a neuron sends an electrical signal, called an action potential, along its output fiber. When this signal reaches the nerve terminal it opens up tiny channels in the terminal membrane, through which calcium ions flow into the interior of the terminal. Within the terminal are vesicles, which are small storage areas containing chemicals called neurotransmitters. The calcium ions migrate by diffusion from their entry channels to special sites, where they trigger the release of the contents of a vesicle into a gap between the terminal and a neighboring neuron. The released chemicals influence the tendency of the neighboring neuron to fire. Thus the nerve terminals, as connecting links between neurons, are basic elements in brain dynamics.

The channels through which the calcium ions enter the nerve terminal are called ion channels. At their narrowest points they are only about a nanometer in width, hence not much larger than the calcium ions themselves. This extreme smallness of the opening in the ion channels has profound quantum mechanical import. The consequence of this narrowness is essentially the same as the consequence of the squeezing of the state of the simple harmonic oscillator, or of the narrowness of the slits in the double-slit experiments. The narrowness of the channel restricts the lateral spatial dimension. Consequently, the uncertainty in lateral velocity is forced by the quantum uncertainty principle to become non-zero, and to be in fact about 1% of the longitudinal velocity of the ion. This causes the quantum probability cloud associated with the calcium ion to fan out over an increasing area as it moves away from the tiny channel to the target region where the ion will be absorbed as a whole on some small triggering site, or will not be absorbed at all on that site. The transit distance is estimated to be about 50 nanometers (Fogelson & Zucker 1985; Schweizer, Betz, & Augustine 1995), but the total distance traveled is increased