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INSTITUTE). The very best of the younger theoretical physicists from all over the world flocked to Copenhagen. Bohr's celebrated need for a "helper" in developing his ideas contributed to the institute's unique atmosphere, subsequently described as the "Copenhagen spirit."

After the formulation of quantum mechanics in 1925, which completed the development of quantum theory, Bohr resumed the philosophical interest of his youth, taking a leading role in interpreting the new theory and pondering its philosophical implications outside the field of physics. In 1927, he introduced the complementarity argument, which he continued to refine and promote for the rest of his life and which still constitutes the basis for the "Copenhagen interpretation" of quantum mechanics (*see* COMPLEMENTARITY AND UNCERTAINTY). Yet his emphasis on an experimental basis for theoretical work did not subside, and beginning in the early 1930s he changed the object of experimental and theoretical research at the institute from the atom as a whole to its nucleus. In so doing, Bohr kept his institute in the forefront of contemporary international physics research.

In 1931 the distinguished Danish philosopher Harald Høffding, one of Christian Bohr's discussion circle, died. Høffding had been the first occupant of the honorary residence at Carlsberg, which was conferred for life by the Royal Danish Academy of Sciences and Letters on the most prominent intellectual in Danish society. The academy chose Bohr as the second occupant. In 1932 he settled in with his wife, Margrethe, and their six sons.

Because several of the institute's guests came from the Soviet Union and Germany, Bohr learned early on about the lack of openness of Soviet society and Hitler's persecution of Jews. Virtually overnight Bohr's institute became a sanctuary for young German physicists unable to return to their homeland—until Bohr was able to find permanent placement for them, most often in the United States. At the end of 1938, physicists at the Copenhagen Institute provided a theory for the recent discovery of fission based on Bohr's liquid drop model of the nucleus, and in 1939, during a stay of several months in the United States, Bohr contributed important insights about the mechanism of the fission process. Yet, as he announced publicly in several lectures and publications, he did not believe in the feasibility of an atomic bomb within the foreseeable future.

Bohr held this view until he arrived in England in October 1943 after escaping from Nazi-occupied Denmark. Once acquainted with the Allied efforts, he came to consider the atomic bomb project feasible and took part in it for the rest of the war. At the same time he carried on his own personal crusade to convince Churchill and Roosevelt that Stalin needed to be informed about the project in order to retain mutual confidence among nations after the war as well as to avoid a nuclear arms race. Bohr's continued insistence on an "open world" among nations, the necessity of which he brought to the attention of statesmen at every opportunity, came to public expression in 1950 in an Open Letter to the United Nations.

Bohr served as a mentor and guide to several generations of theoretical physicists during a particularly important and exciting period for the field. He died peacefully at his home in Copenhagen on 18 November 1962.

Stefan Rozental, ed., *Niels Bohr: His Life and Work as Seen by His Friends and Colleagues* (1967). Abraham Pais, *Niels Bohr's Times, in Physics, Philosophy, and Polity* (1991).

FINN AASERUD

BOLTZMANN, Ludwig (1844–1906), theoretical physicist.

Born in Vienna to a comfortable middle-class family, Boltzmann studied at the university there from 1863 to 1866, when he received his doctorate on the kinetic theory of gases. In 1869 he became professor of mathematical physics at the University of Graz, where he remained until 1873. During this period he spent some months with Robert Bunsen and Leo Königsberg in Heidelberg and with Gustav Kirchhoff and Hermann von *Helmholtz in Berlin. In 1873 he returned to Vienna to the chair of mathematics at the university, which he held for the next three years. In 1876 he relocated again to Graz as professor of experimental physics and began his acquaintance with his future friend but persistent opponent in scientific matters, Wilhelm Ostwald.

The peripatetic Boltzmann went to the University of Munich as professor of theoretical physics in 1890 and then, four years later, to the University of Vienna in the same capacity, to take the chair vacated by the death of his teacher Joseph Stephan. At about the same time, Ernst Mach, who would become both a philosophical and personal adversary, became professor of history and theory of the inductive sciences at Vienna. The friction between the two prompted Boltzmann to accept the offer of Ostwald to move to Leipzig. The hoped-for heaven turned into a hell, owing to disagreements with Ostwald over atomism. Upon Mach's retirement in 1901, Boltzmann returned to his previous post. Emperor Francis Joseph asked him to give his word of honor that he would never accept a position outside the Empire again.

During much of the nineteenth century the belief in the strictly deterministic character of the physical laws was the cornerstone of the physicists' worldview. Boltzmann's work seriously undermined it. In 1877, he published a famous paper, "On the relation between the second law of the mechanical theory of heat and the probability calculus with respect to the theorems on thermal equilibrium," which ascribed only a probabilistic value to the second law of *thermodynamics. A system tends to the state of thermodynamic equilibrium as the most probable, but by no means the only, state the system can reach.

Having realized that the second law could not be interpreted via mechanical principles alone, Boltzmann studied James Clerk *Maxwell's approach to the kinetic theory of gases. In a paper on thermal equilibrium, Boltzmann extended Maxwell's theory of distribution of energy among colliding gas particles, treating the case when external forces are present. He deduced that the average energy of a molecule was roughly equal to kT (where k is "Boltzmann's constant" and T the absolute temperature); larger or smaller energies could occur, but with proportionately lower probability.

Boltzmann next turned his attention to nonequilibrium systems. How could kinetic theory account for the process through which a gas tends towards an equilibrium state? In 1872 he formulated "Boltzmann's H-theorem," which states that H (as the negative *entropy) always decreases, except when the distribution of molecular velocities complies with Maxwell's law. Boltzmann was the first to show that the increase of entropy corresponds to an increasing randomness of molecular motion, as required by Maxwell's distribution law.

These results gave rise to a paradox. If Newtonian mechanics held on the molecular level, interactions between particles had to be reversible, whereas thermodynamic changes on the macroscopic level were irreversible. The answer to this "reversibility paradox" lay in the statistical character of the second law. Nevertheless, the community of physicists became apprehensive about the statistical approach. The reversibility paradox—which was initially pointed out by William *Thomson—formed the basis of a controversy between Boltzmann and his friend and colleague Josef Loschmidt.

The main difficulty lay in accepting the implications of the use of the theory of probability in the formulation of a fundamental law of physics. Boltzmann took on the task of persuading his colleagues that the statistical approach could account legitimately for the macroscopic phenomena of the real world. In developing his position he reached one of his major results, $S = k \log W$, which connected the entropy S of a system in a given state with the probability W of the state. The formula connects a thermodynamic or macroscopic quantity, the entropy, with a statistical or microscopic quantity, probability.

Boltzmann aggressively defended his belief in the atomic structure of matter and tried to reconcile this perspective with the statistical description of macroscopic phenomena. In 1903, he started offering a university course on "Methods and General Theory of the Natural Sciences." It appeared that, at last, he could defend his views in a wider setting. But ill health and recurrence of the depression that sometimes plagued him caused him to take his own life in October 1906, while on vacation with his family at the Bay of Duino, a resort near Trieste.

Engelbert Broda, *Ludwig Boltzmann: Man, Physicist, Philosopher* (1983). John Blackmore, ed., *Ludwig Boltzmann, His Later Life and Philosophy, 1900–1906*, 2 vols. (1995). Carlo Cercignani, *Ludwig Boltzmann: The Man Who Trusted Atoms* (1998). David Lindley, *Boltzmann's Atom: The Great Debate That Launched a Revolution in Physics* (2001).

MANOLIS PATINIOTIS

BOTANICAL GARDEN. A botanical garden differs from pleasure gardens or horticultural establishments in that it exists primarily for scientific research and education. Nonetheless the first gardens combined several functions, especially medicinal and recreational. Religious allegory also played an important role in gardens within the Islamic and Judeo-Christian traditions, drawing on notions of earthly paradises or a former golden age.

The great era of European botanical gardens followed the discovery of the New World. There was a close relationship between the foundation of the six preeminent European gardens in Padua, Leiden, and Montpellier (sixteenth century) and Oxford, Paris, and Uppsala (seventeenth century) and the rise of modern science. Before then, however, many important gardens existed in Mediterranean countries, Arabia, and other parts of the globe in which religious and contemplative functions played a significant role. In the west, the ancient Greeks distinguished between Arcadia, a rustic paradise, and Elysium, the land of the dead where the gods lived. In the Jewish rabbinical tradition the Garden was the blessed part of Sheol where the just awaited resurrection. Early Christians held that humankind was created in an earthly paradise, believed to be the Garden of Eden, and at death would be received into a comparable heavenly paradise where they would dwell with Christ. The Old Testament Song of Solomon and the Mosaic account of creation consequently led in general to the equation of paradise with an enclosed garden.