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Fritz London and the scale of quantum mechanisms

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ABSTRACT

Fritz London's seminal idea of "quantum mechanisms of macroscopic scale", first articulated in 1946, was the unanticipated result of two decades of research, during which London pursued quantum-mechanical explanations of various kinds of systems of particles at different scales. He started at the microphysical scale with the hydrogen molecule, generalized his approach to chemical bonds and intermolecular forces, then turned to macrophysical systems like superconductors and superfluid helium. Along this path, he formulated a set of concepts—the quantum mechanism of exchange, the rigidity of the wave function, the role of quantum statistics in multi-particle systems, the possibility of order in momentum space—that eventually coalesced into a new conception of systems of equal particles. In particular, it was London's clarification of Bose-Einstein condensation that enabled him to formulate the notion of superfluids, and led him to the recognition that quantum mechanics was not, as it was commonly assumed, relevant exclusively as a micromechanics.

1. Introduction

Fritz London introduced his seminal idea of "quantum mechanisms of macroscopic scale" for the first time at the International Conference on Fundamental Particles and Low Temperatures, the first international meeting of physicists after WWII, which was held in July 1946 at the Cavendish Laboratory in Cambridge, UK. London's aim was to explain the low-temperature phenomena of superfluidity and superconductivity on the basis of the new conception of matter that emerged from quantum mechanics. He presented his idea as "a matter of fundamental importance" because it subverted established views about the domain of quantum mechanics (London, 1947, p. 1). His unifying interpretation of the "quantum liquids" or "superfluids" was vindicated in the 1960s, and earned him a place of honour among the spiritual fathers of condensed matter physics (Anderson, 2005; Bardeen, 1972, 1995; Griffin, 1999).[1]

But when and how did London arrive at this ground-breaking idea? He wrote in 1950 that the idea "emerged quite incidentally" in 1934, when he was working on superconductivity in Oxford (London, 1950, p. 3). In a eulogy written shortly after London's death, Lothar W. Nordheim placed the origin of the idea even earlier. According to Nordheim, the idea came to London "naturally" when he was working on molecular physics in Berlin in the late 1920s and early 1930s, and then became "the leitmotif for all his later work." (Nordheim, 1954, p. 16). Jean Matricon and Georges Waysand, in their history of superconductivity, interpreted Nordheim's words to mean that London's "great intuition of quantum phenomena at the macroscopic scale" was "the guiding principle" ("le fil directeur") of all London's studies, although they admit that London did not mention explicitly this intuition until much later (Matricon & Waysand, 1994, p. 109). London's biographer, Kostas Gavroglu, set forth the thesis that the conception of superfluids was the fulfillment of London's lifelong, albeit timid, commitment to a specific agenda (Gavroglu, 1995, 2001; Gavroglu & Simões, 2012). According to Gavroglu, London took "a very strong antireductionist stand" already in his pre-university forays into physics and philosophy, and never abandoned it, even though he never expressed it except in some very early unpublished writings (Gavroglu, 1995, p. 10). Gavroglu claims that London remained an antireductionist at heart even after he and Heitler effectively launched the program of reducing chemistry to quantum mechanics. While working on a quantum-mechanical theory of chemical bonding, London "started to articulate an agenda based on the non-reductionism of quantum

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[1] In 1946, London used the expression "quantum liquids" only (London, 1947, p. 3). He introduced the term "superfluides", alongside "liquides quantiques", in an article in French in 1949 (London, 1949, p. 442). *Superfluids* is the title of the book he published in 1950 (London, 1950). John Bardeen repeatedly acknowledged London's influence on his work. Upon receiving his second Nobel Prize in physics in 1972 for the microscopic theory of superconductivity, Bardeen credited London for the insight that superconductivity was "a quantum phenomenon of a macroscopic scale." (Bardeen, 1972, p. 54). Today, physicists routinely classify superconductivity and superfluidity, together with Bose-Einstein condensation and lasers, as "macroscopic quantum phenomena". London never used this expression.

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chemistry to physics." (Gavroglu, 1995, p. 74). This quiet but persistent "abhorrence of reductionist schemata" would be finally "substantiated years later, in the mid-1930s, in London's first elaborations of his remarkable notion of macroscopic quantum phenomena." (Gavroglu, 1995, p. 14). Gavroglu defines London's antireductionism as "abhorrence for any approach that had as its strategy the formulation of the equations of motion for the minutest constituents as a necessary step for deriving the behaviour of the whole." (Gavroglu, 1995, p. 10) He clearly recognizes that there was a conflict between London's pioneering of quantum chemistry and "the antireductionism which was so pronounced in his philosophical thinking". This conflict supposedly landed London in a "methodological quagmire." Still, according to Gavroglu, "London refused to accept reductionism." (Gavroglu, 1995, p. 170).

My analysis draws from Gavroglu's authoritative biography as concerns London's life events, but I offer a different reconstruction of the birth of the idea of macroscopic quantum mechanisms. To be sure, germs of the idea can be found retrospectively in London's work from the late twenties onward in his studies of the quantum behaviour of aggregates of particles in increasingly large systems. It is understandable that after 1946 he would be inclined to reinterpret those germs in hindsight as embryonic versions of his new idea. Nonetheless, the idea itself was the layered result of a slow realization, not an early intuition or the goal of a pre-set agenda. Despite three forced emigrations and consequent disruptions in London's life and career, his research exhibited a remarkable continuity. He started from the application of the then very new theory of quantum mechanics to the microphysical scale with the hydrogen molecule, then moved to a larger scale with chemical valence and intermolecular forces, and finally tackled macrophysical systems like superconductors and liquid helium. All along, he aimed to provide microphysical explanations based on quantum mechanics. Not until the 1940s did London give expression to unconventional thoughts on the scale of quantum mechanisms. On the contrary, the sparse and indirect remarks of his that touched on the matter reflected the views prevalent among his colleagues. His earliest allusion to the possibility of an "enlargement of the quantum effects" is found in a private letter of 1941 (London, 1941). And only on the occasion of the Cambridge conference, before an international audience that brought together high-energy microphysics and low-temperature macrophysics, did he articulate the claim that the superfluids represented a class of phenomena "where quantum mechanics would directly reach into the macroscopic world." (London, 1947, p. 1).

In what follows, I will examine some threads of London's research across the different stages of his life and work. My aim is to trace the evolution of his views, and to explore factors and circumstances that catalyzed the convergence of these threads into the single innovative interpretation of the superfluids. I will start by investigating London's notion of a quantum mechanism. I will then retrace the origins of his concept of order in momentum space, and the first appearances of the idea of quantum mechanisms of macroscopic scale.

2. What is a quantum mechanism?

London opened his address at the Cambridge conference with the claim that, if confirmed, the existence of quantum mechanisms of a macroscopic scale would be of fundamental importance because it would dispel a widely-held misconception about the domain of quantum mechanics, a misconception that he implicitly admitted to sharing until recently:

> We have been used to considering quantum mechanics generally to be important only for the atomic and subatomic world and linked with the world of our perception only indirectly, namely through the medium of averages over thermally disordered assemblies of micro-mechanisms, the properties of which mechanisms are known to be fundamentally different from the machines which we can see and touch (London, 1947, p. 1).

Similar remarks about the need to correct the prejudice about the scale of quantum mechanisms became persistent and dominant, a clear leitmotif, in his subsequent work, but they are notably absent from all his previous writings. In a review article of 1929, he had presented a version of the history of his field according to which "quantum theory was indeed initially developed primarily as a theory of the structure of individual atoms from their constituents." (London, 1929, p. 516). He revisited this narrative in his 1950 book, *Superfluids*, this time using it to give emphasis to the novelty of the idea of the macroscopic reach of quantum mechanisms:

> In fact, the differential equations of macroscopic physics betray no trace of the quantum character of the basic laws of nature. They were actually discovered on an atomistic basis a long time before quantum mechanics was discovered. Thus it has become quite common to regard quantum mechanics as a "micro-mechanics," that is, as relevant *exclusively* to the understanding of the mechanisms of the submolecular world. (London, 1950, p. 2, emphasis in original)[2]

This version of history would have surprised the founders of quantum theory, as for example Max Planck and Albert Einstein, who had conceived of the quantum expressly as a tool to bridge the microscopic and the macroscopic levels with statistical methods. They had thus derived equations that described macroscopic systems in radiation theory and low-temperature physics. The first to use the term "quantum mechanics" was probably Einstein, and he used it in 1922 precisely to refer to a microphysical theory of superconductivity, or more accurately, the lack thereof (Einstein, 1922; Sauer, 2007). Planck, Einstein, and other pioneers of the old quantum theory would hardly have considered it necessary to argue for the idea that quantum mechanisms—processes governed by the quantum hypothesis, as they understood them—can manifest themselves on the scale of large objects. For them, it was a foregone point.

London's narrative was a projection of his own perspective. He grew up professionally with quantum mechanics, having little exposure to the original statistical approach of the old quantum theory. Quantum mechanisms of macroscopic scale were a new idea to him because he had a specifically quantum-mechanical understanding of what constituted a quantum mechanism. He was correct to note that, ever since quantum mechanics was formulated in 1925–1926, it had become customary to treat *it* exclusively as micromechanics. Quantum mechanics was indeed born as a theory of individual particles. It originated mainly from the application of the quantum hypothesis to spectroscopy and the study of atomic structure according to the Bohr-Sommerfeld model. It was the expression of a shared project of building a new physics on the blueprint of classical mechanics, namely, starting from the mechanics of an individual particle, a microphysical body, and then expanding it to multi-particle systems by means of dynamical methods. Physicists of London's generation and milieu assumed

[2] London's account was later echoed by John Bardeen, who wrote, "Quantum theory was derived to account for the properties of atoms and molecules at the microscopic level. It was Fritz London who first recognized that superconductivity and superfluid flow result from manifestations of quantum phenomena on the scale of large objects." (Bardeen, 1995, p. 267).