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David Bohm and collective movement

THIS PAPER CONTINUES an earlier investigation into the history of some fundamental concepts in modern quantum physics of condensed matter and their underlying philosophy.[1] Research on condensed matter—solids, liquids, and plasmas—presently constitutes a broad area of studies, theoretical and experimental, and is arguably the most active branch of fundamental physics today. Yet the field does not have a reputation of being philosophical, appearing, on the contrary, rather technical and pragmatic, often phenomenological, oriented towards applications, and bureaucratically classified as applied "material science." Unlike quantum mechanics, condensed matter physics does not stir a major epistemological controversy, and unlike high energy physics it does not claim to be the most fundamental of all sciences. Its relatively low profile and down-to-earth image are upheld by the majority of practitioners, physicists themselves, although some of them complain about the resulting loss in the field's prestige and limelight, especially among

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The following abbreviations are used: AIP, Center for History of Physics, American Institute of Physics; Bohm-Wilkins, Oral History Interviews with David Bohm, conducted by Maurice Wilkins (1986), 16 tapes, unedited transcript (AIP and DBP); DBP, Papers and Correspondence of David Bohm, Birkbeck College Library, University of London; *JETP*, *Zhurnal eksperimental'noi i teoreticheskoi fiziki* (Moscow); *JoP*, *Journal of physics* (Moscow, 1939-1947); LCP, *Collected papers of L.D. Landau*, ed. and with an introduction by D. ter Haar (New York, 1965); *PR*, *Physical review*.

[1] Alexei Kojevnikov, "Freedom, collectivism, and quasiparticles: Social metaphors in quantum physics," *HSPS, 29:2* (1999), 295-331.

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lay audiences.[2] Correspondingly, the physics of condensed matter has received less attention than warranted from historians of science. A closer look into its early history, from the founding period of the 1920s through the 1950s, when the discipline was still small and its main ideas nascent, reveals a more intriguing picture.

Many of the basic concepts now firmly established were controversial when first introduced. One of the most basic of the disagreements concerned the fundamental problem of freedom. Competing approaches to complex physical phenomena in solids and liquids relied on different hypotheses about how much, and what kind of freedom was available to microscopic constituents inside densely packed bodies. These constituents—atoms, ions, and electrons—were usually assumed to be known from other branches of physics, but they produced new and very strange effects when interacting in large assemblies. Physicists who invented the first models for these effects had to make non-trivial assumptions about the states of freedom and relationships between particles. The variety and complexity of situations in real bodies made the problems almost as difficult as sorting out the relationships and states of freedom in the human world. At least physicists' intuitions and hypotheses about the behavior of particles were sometimes suggested by their life experiences in real societies and by their general views regarding the problem of freedom.

Another major issue, collectivism, provided intuitions for a group of condensed matter theorists, who tried to solve the basic problem of freedom for atoms and electrons along collectivist lines. Initially, only a minority of physicists, most of them socialists, designed physical and mathematical models for the collective behavior of microscopic particles. Their models differed according to the specific physical problem and the various meanings of "collectivism" in socialist thought. The products of these collectivist approaches varied too, but the most general one, important across the entire discipline, was the concept of "quasiparticles," or "collective excitations." These new fundamental entities behaved in many ways like particles, but were constructed (or supposed to be constructed) out of the movement of a great many atoms or electrons. Quasiparticles helped scientists conceive the complexities of many-body systems, and during the 1950s they became the standard tool of the discipline. Many experiments confirmed their existence in nature. The number of different kinds of quasiparticles discovered, increased over decades to a couple of dozen. Taken realistically, quasiparticles gave condensed matter physics its own set of fundamental ontological entities at the microscopic level, no less fundamental, some would say, than elementary particles in high-energy physics.

The first part of this study dealt with several early examples of quasiparticles in solid bodies—phonons, holes, excitons, and polarons—and their principal authors, Soviet physicists Yakov Frenkel, Igor Tamm, and Lev Landau.[3] This paper

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[2] P.W. Anderson, "More is different," *Science, 177* (1972), 393-396, argues for a different image for condensed matter physics.

[3] Kojevnikov (ref. 1) and Alexei Kojevnikov, "Landau, physicist and revolutionary," *Physics world, 15:6* (2002), 35-39. See also Karl Philip Hall, *Purely practical revolutionaries: A*

carries the story to the United States and from the solid state to plasma. It focuses on David Bohm's research project around 1950, which laid the foundation of the modern theory of plasma and led to the introduction of another quasiparticle, the plasmon. Bohm's case bears some similarities to those of his Soviet colleagues. Like them, he was a socialist, although of a different kind, and a strong believer in collectivism. Like them, he used collectivist notions in his attempts to understand the behavior of particles in dense physical systems, the most important of these notions in his case being "collective movement." Another suggestive similarity is that all of them had to struggle for their personal freedom. Although Bohm's situation was not as grave as Landau's, who spent an entire year behind bars with only a slim chance of survival; still, the experience of McCarthyist persecution and arrest added a new dimension to Bohm's thoughts on the complexities of freedom, just as the Stalinist purges had done for Landau.[4] Their ideas and approaches to many-body physics evolved along similar collectivist lines, to a large degree independently.

"Some people cannot march with others"

David Joseph Bohm was born in 1917 in Wilkes-Barre, Pennsylvania, to a dysfunctional family of Jewish immigrants. Bohm's father owned a small furniture store and, hoping that his elder son would some day become "the greatest furniture dealer in town," tried to discourage the boy's early interest in impractical "scientism." David resisted the parental pressure and ridicule: dreams about science became his teenage rebellion, offering an escape from conflicts at home, an oppressive mood at school, and the anti-intellectual, intermittently anti-Semitic atmosphere in town. He was fascinated by science fiction, the ideas of space travel, the fourth dimension, and unlimited atomic energy. Trying to improve his deficient physical coordination, Bohm reconstructed in his mind complex spatial movements of his own and other physical bodies, a mental exercise that developed into an exceptional cognitive ability. His early interests embraced models of airplanes and radio sets, attempts at making patentable inventions, and metaphysical pictures of space, time, and atoms. The father did pay for his son's education at Pennsylvania State College, and Bohm used the opportunity to read and study well beyond the modest requirements of the curriculum. In his last year at college, Bohm won a prize in a mathematical competition, a fellowship of $600 that allowed him to start graduate studies at Caltech in September 1939, just as the second world war erupted in Europe.[5]

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history of Stalinist theoretical physics (Ph.D. dissertation, Harvard University, 1999), for a perceptive and detailed analysis of Landau's physics in its political context.

[4] Silvan S. Schweber recalled "1950, that fateful, traumatic year for Dave—the scars of which never healed, and they manifested themselves in a certain loss of control. The character of his physics was affected by it." Schweber, in Memoriam David Bohm (DBP: A 14).

[5] F. David Peat, *Infinite potential: The life and times of David Bohm* (Reading, MA, 1997), 5-33. See also Bohm-Wilkins, 8-9, 18, 31, 43-57, 66.

Caltech disappointed Bohm: he felt that the overwhelming emphasis on competition and on technical problem-solving got in the way of thoughtful understanding and inquiry. He thus gladly accepted an invitation from J. Robert Oppenheimer in 1941 to transfer to Berkeley, where in the circle of Oppenheimer's students he found a much more congenial atmosphere for his way of learning. Oppenheimer was a very inspiring teacher of quantum mechanics, with a philosophical touch so dear to Bohm's mind ("more interested in general ideas than anybody at Cal Tech"). Yet the student and the professor did not become close. Soon after Bohm's arrival in Berkeley Oppenheimer began devoting most of his time to the nuclear energy project and working in Los Alamos. Bohm learned mostly from his private reading and long discussions with fellow students, especially Joseph Weinberg. He got his Ph.D. in 1943 for calculations on the scattering of protons and deuterons, the results of which were classified for the use in the ongoing Manhattan Project. Through the rest of the war, Bohm worked at the Berkeley Radiation Laboratory.[6]

Oppenheimer's request to have Bohm transferred to Los Alamos was not approved by the Manhattan Project's security officers. The ostensible reason was that Bohm had relatives in Nazi-occupied Eastern Europe; another, undeclared cause was his leftist political activity. In spring 1943 Bohm took part in an attempt to unionize the Radiation Laboratory, where FAECT (Federation of Architects, Engineers, Chemists, and Technicians) established a local chapter with some thirty members. Although the union's objectives were cooperation rather than confrontation ("to unite the personnel into a cohesive group in order to: 1. Maintain, protect, and advance economic welfare of all employees; 2. Increase the project's contribution to the war effort by promoting individuals' and group efficiency"), the authorities opposed the attempt and suspected communist influence. Some members of the Berkeley chapter, including Bohm, were either close to the Communist Party or its members.[7]

Bohm's passion for politics—more for thinking and discussion than for action—had been awakened during his Pennsylvania years. He believed strongly in democracy and in science as a way of material progress and improvement in political life. An additional interest in socialism emerged gradually, inspired by Bohm's observations of the conditions of life in his native town, a working-class community of poverty-stricken miners, during the Great Depression. Late in his life he recalled the depression as a crucial event, which demonstrated to him that in a real

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[6] Interview with David Bohm, notes by Martin Sherwin, 1979 (DBP: A 116); Peat (ref. 5), 64; Bohm-Wilkins, 180-186, 242.

[7] On FAECT and its Berkeley chapter see the Military Intelligence reports in DBP: A 115; *In the matter of J. Robert Oppenheimer: Transcript of hearing before personnel security board and texts of principal documents and letters* (Cambridge, 1971), 13, 119-120; Russell Olwell, "Physical isolation and marginalization in physics: David Bohm's Cold War exile," *Isis*, *90* (1999) 738-756; and *Un-American activities in California*, California Legislature, Senate, Third Report [Joint Fact-Finding Committee on Un-American Activities in California], 1947 (Sacramento, 1947), 201-219.

crisis people cannot survive by relying on their individual efforts alone. The shock from that experience destroyed Bohm's earlier illusions about the efficiency of individualism and turned his political philosophy towards collectivism: "[I]n the beginning I believed in all the conservative ideas about individualism, but then the depression made me begin to question those and [say] that the society must have some responsibility not only for the poor people, but to give everybody a chance. You can't just leave it to the law of the jungle."[8]

By the mid-1930s, Bohm's greatest worry was the growing threat of fascism, which he regarded with horror as "a total threat to civilization." He watched the western democracies acquiesce in the rise of the fascist tide in Europe hoping that the latter would suppress communist movements. During the Spanish Civil War, it seemed to him "as though the Russians were the only ones that were really fighting" against international fascism, assisting the republic in its losing struggle.[9] He was alarmed by the growth of the anti-Semitic, pro-Nazi right in the U.S., and feared that the wealthy elites would betray the democratic ideal.[10] These political developments contributed to Bohm's growing acceptance of socialism. After he arrived in Berkeley in 1941, his circle included many who thought as he did. The Soviet Union was then once again—after the interlude of the non-aggression pact with Nazi Germany—leading the international fight against fascism. Bohm was ready to identify himself as socialist and Marxist.

The existing information on Bohm's communist affiliation is sketchy. If the date November 1942, provided by his biographer, is correct, then he joined the party at the most critical juncture of World War II, the battle of Stalingrad, which he monitored daily. According to Bohm's later statements, he left the party after about nine months. He hinted on different later occasions at several possible reasons for his disenchantment. The intellectual satisfaction did not meet his expectations ("the meetings were interminable"), and instead of the "unity and comradeship" he desired, he found intrigues and power struggles. In any case, Bohm was scarcely capable of accepting and following the communists' strict party discipline. As much as he longed throughout his entire life to be part of a collective, he was also, in the perceptive definition of a desperate college drill sergeant, one of those "people who just can't march with others."[11]

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8. Bohm-Wilkins, 68-69.

9. Interview with David Bohm, notes by Martin Sherwin (ref. 6).

10. "[G]radually, I began to see that the American society wasn't all that free, that lot of this was only lip service to freedom….I felt that in America you had potential sympathy for Nazism…and a lot of people who were fascistically oriented. I could see that all this talk about freedom and free enterprise was not to be taken very seriously, that these people wanted freedom to make money for themselves and they didn't care what happened to other people. They used very repressive measures….They created an atmosphere which was very conformist." Bohm-Wilkins, 116, 173; also 83-92, 119, 215-220.

11. Interview with David Bohm, notes by Martin Sherwin (ref. 6); Peat (ref. 5), 30, 58; B.J. Hiley, "David Joseph Bohm, 20 December 1917-27 October 1992," Royal Society of

Other reasons militating against a long sojourn in party the include Oppenheimer's request to his students to stay away from political activism while doing military research and the crackdown on FAECT. Once the Berkeley branch of the union was established in spring 1943, its activities and contacts with the area's communist organizers came under the surveillance of the War Department's Military Intelligence Service. Lt. Colonel Boris T. Pash, later of Alsos fame, in 1943 was the chief of the Counterintelligence Branch of the Western Defense Command. He supervised the follow up of a surveillance report that a certain scientist "Joe" from the Radiation Laboratory had paid a visit to the prominent communist official and hero of the Spanish Civil War, Steve Nelson, and had dictated some formula or piece of technical information Nelson supposedly passed on to a Soviet diplomat. Pash believed that his primary suspect, Giovanni Rossi Lomanitz, and probably also Lomanitz' friends Bohm and Weinberg, belonged to the Communist Party, and recommended to General Groves that Lomanitz' draft deferment be cancelled. Having received Pash's report, which declared the FAECT branch "an organization known to be dominated and controlled by Communist Party members or Communist Party sympathizers," Groves decided in August 1943 that "immediate action must be taken to stop the activities of the union." This call was conveyed to Philip Murray, President of the Congress of Industrial Organizations to which FAECT belonged, who had the branch at the Berkeley Radiation Laboratory closed.[12]

Bohm would not have learned about most of these behind-the-scene activities until much later. At the time, his main worry was about the drafting of Lomanitz, which he undersood as political persecution linked to Lomanitz' especially active role in the unionizing at the Radiation Laboratory. Bohm and Weinberg shared this conviction and their own fears of similar persecution with Oppenheimer, who advised them to stay away from active politics. Bohm's decision to terminate his Communist Party membership coincided with these events, which took place during the nine months after November 1942. Whether this was the reason or not, Bohm severed his ties with the organized communist movement while remaining a convinced Marxist with a special interest in the philosophy of dialectical materialism. Part of the attraction of the Marxist worldview, as he later tried to explain to an American consular official, was that it "opened up all kinds of vistas for me, both in my scientific research and in my thinking about other fields."[13]

London, *Biographical memoirs,* 1997, 107-131, on 109; Bohm's statement to U.S. Consul in London, 23 Mar 1960 (DBP, I thank Shawn Mullet for information about this important document); Bohm-Wilkins, 136.

[12] Military Intelligence reports on FAECT (DBP: A 115); Pash's testimony in *In the matter* (ref. 7), 809-812.

[13] Statement to U.S. Consul in London, 23 Mar 1960 (DBP).

A failed containment

The scientific project with which Bohm became involved in 1943 dealt with plasma. That year, a contingent of British physicists arrived in the U.S. to work on the Manhattan Project. Some of them, headed by H.S.W. Massey, came to the Berkeley Radiation Laboratory to set up an experimental investigation of electrical discharges in magnetic fields. Their immediate goal was to improve the industrial process of electromagnetic separation of uranium isotopes, which had started at Oak Ridge before a detailed scientific investigation of the underlying physical processes had been completed. The narrow focusing of ionic beams was essential for the success of the industrial process. Space-charge effects, or the fact that electrically charged ions in the beam repel each other, spread the beams. The Massey team undertook a systematic study of the behavior of plasma, the gas of ions and electrons, in the magnetic field, in the hope of developing effective methods of containment of charged particles. Bohm de-facto became the group's house theorist.

As they subjected plasma to careful investigation, they discovered strange behavior and some new unexpected phenomena, which essentially destroyed hope for significant improvements in electromagnetic separation. Plasma turned out to be a capricious medium, unstable and unpredictable, and also effectively resistant to manipulation and containment. The bulk of research reports submitted by the group to the Manhattan Project were declassified and published after the war. The material contains experimental findings by British physicists and Bohm's theoretical attempts to understand the sources of difficulties encountered. The experimental setup had a beam of electrons passing vertically through a chamber containing rarefied argon. The electrons split the atoms of gas they encountered into ions and secondary electrons, which together formed the plasma, a gas of positively and negatively charged particles. Through an observation window, the experimenters could see the bright column of the primary beam surrounded by a fainter glow of plasma of ions and electrons.[14]

To try to contain the plasma, Massey's team placed the entire chamber in a strong vertical magnetic field. This arrangement did not prevent ions and electrons from moving vertically, but was supposed to constrain their horizontal movements in small circles. The estimated radii of the horizontal rotations of electrons were about 2 mm. The strategy failed to work. Although the plasma could be made somewhat narrower with the help of the magnetic field, plasma electrons still moved relatively easily in horizontal directions and drifted away from the primary beam. One known contributing factor was collisions between the electrons. When two electrons collide, both their circular trajectories shift a little and after many ran-

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[14] David Bohm, "Qualitative description of the arc plasma in a magnetic field," in A. Guthrie, R.K. Wakerling, eds., *The characteristics of electrical discharges in magnetic fields* (New York, 1949), 1-12.

dom collisions can drift away from the original location. Yet calculations showed that diffusion by collision took place too slowly to account for observed effects.

Inhomogeneity or instability in the magnetic field can also cause the electrons' orbits to drift. John Backus, a physicist on the team, suggested that the charged particles of plasma could disturb the external field, producing fluctuations of sufficient strength to explain observations.[15] Probably at this point the experimentalists decided to consult a theoretician. Bohm set out to imagine a mechanism to cause the Backus effect. It turned out to be very complex. In fact, it was one of those strange "collective effects," that could not be accounted for by the existing, rather simple, theoretical ideas about plasma, but required an entirely new level of sophistication, physical models, and mathematical technique. As Bohm's thoughts developed, plasma started to look to him "almost like a living organism."[16] On the one hand, it preserved its autonomy, effectively screening out external charges inserted into it. It was also internally unstable: certain small irregularities and fluctuations in the electron density grew uncontrollably into a kind of turbulence, stabilizing at some higher level only due to non-linear effects. It possessed capabilities for self-organization: some of these stabilized movements involved masses of electrons coordinating their movements over long distances and producing the phenomenon of plasma oscillations, which had been known since the 1920s but not properly understood. And finally, these oscillations, collective self-organized actions of electrons, could carry some of the electrons away, defying the forces of containment.

Apparently, as became his habit, Bohm worked out the new model of plasma at first on the intuitive, visual level, only later developing a mathematical formalism.[17] Even when preparing the wartime reports for publication in 1949, he mentioned that he was still refining the quantitative theory. But he had confidence in the basic qualitative picture and offered some numerical estimates. The most important of these estimates was the diffusion coefficient for electrons spreading in directions transverse to the magnetic field: "By investigating the dynamic theory of the plasma, it has been shown that when electrons move across the magnetic field by collision diffusion the plasma is unstable. If a small deviation from the steady state is accidentally produced, the system does not return to its initial condition but instead begins to oscillate with an amplitude increasing exponentially with time. Of course, the amplitude of these oscillations is ultimately limited by new processes that first become appreciable at large oscillation amplitudes. The most important of these processes is precisely the electron drain brought about by the oscillating fields, which rapidly increases the diffusion coefficient $D_\perp$. It may be shown mathematically, and the result is very reasonable physically, that diffusion tends to damp plasma waves. Thus at a certain mean amplitude the diffusion coefficient will provide just enough damping to stop the exponential increase, and

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[15] Bohm-Wilkins, 250.

[16] Bohm-Wilkins, 247.

[17] Bohm-Wilkins, 139.

the system will oscillate in a steady state. With the aid of the theory the value of $D_\perp$ at which this balance occurs can be calculated. It is

$$D_\perp = \frac{10^5}{16H}\left(\frac{kT_e}{e}\right), \qquad (1)$$

where H is in thousands of gauss and kT_e/e is in volts. The exact value of $D_\perp$ is uncertain within a factor of 2 or 3."[18]

Bohm's estimate turned out to be astonishingly precise. He never published his calculation and for more than a decade nobody else could derive the formula. But as study of plasma containment picked up in the 1950s in connection with the new military project on controlled thermonuclear fusion, experimental physicists were constantly finding their results in agreement with Bohm's theoretical prediction including the exact numerical coefficient 1/16.[19] Bohm diffusion was the chief obstacle to containment in early thermonuclear plasma devices, stellarators, and the main source of experimental obstacles to controlled fusion. By then, however, Bohm had already gone into political exile and was not available for consultation.

As the war ended, most physicists who worked on the Manhattan Project returned to academic positions and changed their research preoccupations to civilian topics. Bohm's reputation as one of Oppenheimer's most brilliant students helped him get an offer from Princeton University, where he became an assistant professor in 1947. In the mean time, like many others, Bohm had to choose a new research topic. He tried several problems, including the theory of the synchrotron, infinities in quantum electrodynamics, superconductivity, and a theory of non-point elementary particles. Oppenheimer and several others advised him to work on renormalization and nuclear physics, then hot, fundamental, and career-friendly topics. Bohm ignored the well-meaning advice: he was already developing an aversion to nuclear physics as too closely related to the military, fundamentally boring, and intellectually uninspiring.[20]

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18. David Bohm, E.H.S. Burhop, and H.S.W. Massey, "The use of probes for plasma exploration in strong magnetic fields," in Guthrie and Wakerling, eds. (ref. 14), 13-76, on 64-65.
19. "He never published a derivation, and when Lyman Spitzer once asked him about it, he thought that it was just a "back of the envelope" calculation. On the other hand, the Bohm formula, even with its *ad hoc* coefficient of 1/16, provided a frustrating but extraordinary fit to a decade of data from B and C stellarators at Princeton." Thomas H. Stix, "In memoriam David Bohm" (DBP: A 13). See also, R.F. Post, "High-temperature plasma research and controlled fusion," *Annual review of nuclear science, 9* (1959), 367-436.
20. "Every time I hear the word 'nuclear physics,' it calls up to my mind an image of the most boring possible subject in the world. The surest way to discourage me from working in the quantum theory would be to continually remind me that it might be useful in nuclear physics." Bohm to Melba Phillips, late 1951 or early 1952 (DBP: C 46). See also Bohm-Wilkins, 304-305, 320.

In fact, Bohm disapproved of many trends in the postwar physics community. He thought it conformist, mindful of hierarchy but driven by mindless fashion, and conservative intellectually. Oppenheimer, the once revered teacher, suggested a certain problem to Bohm on the ground that Dirac, a luminary, thought it promising, but withdrew the recommendation after Dirac lost interest in it. Putting aside their ability to think independently, physicists were running after fads. They appreciated technical skills in calculating effects on the basis of already existing theoretical conceptions, and devalued as "unprofessional" searching for unusual ideas, asking deep questions or thinking about foundations. Bohm could not march along: "I felt that was really very dull. It was heavy and boring....I would have felt at the time...that if I had the qualities which enabled me, like Oppenheimer, to join the bandwagon and do what the majority were doing, then probably I would never have become a physicist. I would have become a furniture man. I would have become a businessman and perhaps one of the leading furniture dealers in Wilkes-Barre."[21] A few years later, his non-conformism would cost Bohm his standing in the physics establishment, at the same time that his political non-conformism caused him trouble with the political establishment in Cold War America.

At Princeton Bohm concentrated increasingly on plasma as his own, independent research subject. Plasma was not considered a prestigious, fundamental topic, in part because it did not seem to have a military importance. War-time studies of plasma had not helped the Manhattan Project; their military relevance became clear only a few years later, with the start of the H-bomb race. In Bohm's eyes, however, plasma was more fundamental than atomic nuclei, in particular from the philosophical point of view: "First of all, it was a sort of autonomous medium; it determined its own conditions, it had its own movements which were self-determined, and it had the effect that you had collective movement, but all the individuals would contribute to the collective and at the same time have their own autonomy."[22]

Bohm's early papers on the physics of plasma reflect his preoccupation with the question how electrons as free particles could coordinate their movements. Combining collectivism with individual freedom had a very strong personal appeal to him. His experience in a communist group and in the abortive unionizing attempt in Berkeley had not offered him a satisfactory solution. Electrons in plasma, however, managed to achieve collective action. They were practically free particles, independent of one another, but as a result of subtle interactions within a large group, they developed patterns of organized coherent movement. How exactly they did so, became the topic of Bohm's mathematical calculations over some ten years, 1948-1958. Perhaps once again, as in his early years, he was interiorizing a problem, whose solution evaded him in his personal and social life, by developing an elaborate mental picture and finding a solution in his own mind. Bohm's thoughts were so intense that, by reading his papers on the physics of plasma, the

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21. Bohm-Wilkins, 304-308.
22. David Bohm, interview by Lillian Hoddeson, 1981, 4 (AIP).

evolution of his general ideas on the problem of collectivism and freedom can be traced.

Organized movement

"The plasma became very interesting to me. I could see that this was a kind of analogy to the problem of the individual and society. You had in the plasma what I called collective behavior….When all the electrons move together, they produce an electric field that draws them back so that they'll oscillate…in a coherent way…I call that a collective movement…The question was how was this collective motion maintained in spite of the random basis of the electrons….[T]his was the kind of interesting social question….[I]t was a self-sustaining motion in such that each electron had its freedom, apparently, to do whatever it would do. But nevertheless, because of the effect of the collective long range effects, each electron was modified a bit and was able therefore to add together to produce the…collective motion....I saw that as a model of society where I wanted to begin to understand the relation of the individual and the collective. Where one did not greatly interfere with the individual freedom and yet could understand collective action."[23]

Bohm made this statement at the end of his life, long after he had abandoned Marxism, and so did not discuss the specifically Marxist connection. But the message is entirely consistent with similar remarks he made on various occasions throughout his life, in interviews and published work, as well as with the language and content of his research on plasma during the 1950s. Of course, in his physics papers, Bohm did not announce connections with social philosophy in so straightforward a way. That would have been inappropriate for the genre of mathematical physics, counterproductive as a strategy to convince fellow physicists, and politically self-incriminating in the times of rampant anti-communism. But even in his mathematical publications, he relied heavily on collectivist and other political terminology, made occasional analogies to social phenomena, and attempted to understand dialectically the relationship between collective and individual in the case of electrons in plasma. Though less explicit, Bohm's physical papers are more informative, containing more specific details about his political philosophy at the time of writing than his later recollections do.

Bohm's language before 1950 was not yet "collectivist," at least not in the published texts. He relied on a different, trade-unionist metaphor, "organized movement." Neither his physical nor his political ideas were fully developed, but he had, at least, the unsuccessful experience of the union organizing behind him. His first attempt to translate that experience into physical ideas was not very successful either. Before Bohm published his main papers on plasma, he suggested that a similar approach could solve the riddle of superconductivity in the theory of metals.

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[23] Bohm-Wilkins, pp. 253-254. See also B.J. Hiley, "David Joseph Bohm, 20 December 1917—27 October 1992," Royal Society, *Biographical memoirs* (1997), 107-131, on 110-111.

The system of electrons in a metal is in some important aspects similar to that of electrons in plasma, which made a number of theorists, including Bohm, hopeful that both problems could be treated by similar methods. Both systems can be analyzed as a dense gas of rapidly moving electrons mixed with approximately the same number of positive ions, so that the medium on the whole is electrically neutral. In metals, the ions are largely fixed in the periodic crystal lattice, while in plasma they move almost freely as the electrons. However, owing to their much larger masses, ions in plasma move hundreds of times slower than electrons. At the beginning of plasma theory, physicists typically dealt with rapidly moving electrons while considering ions to be practically at rest. With regard to electronic calculations, in this approximation metals and plasma looked comparable.

Mathematical difficulties looked similar, too, because in both cases physicists did not know how to account for a gas with many-particle interactions. The existing methods derived mainly from classical kinetic theory, in which electrically neutral atoms of a gas interact only when they directly collide. In gases, where atoms are rare, most collisions involve only two atoms. Ignoring the rare and more complex occasions, when three or more atoms simultaneously collide at one point, physicists could simplify enough to treat the problem mathematically. The simplifying assumption held for rarefied gases with electrically neutral atoms, but not for the electron gas, which, in plasma and metals alike, consists of charged particles interacting via long-range Coulomb forces. Although such forces between distant particles were much weaker than impact by short-range collision, each electron felt the influence from not just one other particle at a time, but from a great many of them simultaneously. The existing mathematical formalism, however, was only good for treating one-on-one interactions. Bohm felt that he was on the right path to understanding how many-body interactions worked in plasma. This also gave him hope that it would be possible to explain the most puzzling property of metals, their superconductivity at low temperatures, on similar lines.

Many seemingly insoluble problems found miraculous resolution after the arrival of quantum mechanics in the 1920s; in many other cases physicists could explain why quantum approaches were meeting with difficulties. Superconductivity did not fall into either of these categories and distinguished itself as the most resistant and irritating challenge for quantum theorists. Adding insult to injury, one of the strictest proofs the theory could produce implied that there could be no such thing as superconductivity. The "Bloch theorem" stated that an electron's wave function corresponding to the state with zero electric current always has a lower energy than a wave function with non-zero current, which would mean that the superconducting state cannot be stable, and that the current cannot stay indefinitely, in appalling disagreement with experimental evidence.[24]

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24. Edward Philip Jurkowitz, *Interpreting superconductivity: The history of quantum theory and the theory of superconductivity and superfluidity, 1933-1957* (Ph.D. dissertation, University of Toronto, 1995); Kostas Gavroglu, *Fritz London: A scientific biography* (Cambridge, 1995).

Many physicists hoped that the Bloch theorem held only for the one-electron wave function (or for an assembly of independent electrons), but not for interactions between electrons. Bohm entertained this hope, but like Bloch and several others demonstrated by a rather simple calculation that the theorem remains valid even when the energy of electronic interaction is added to the Hamiltonian. Bohm published such a demonstration in 1949, adding, on a somewhat desperate note, that it still might be possible to make superconductivity long-lasting rather than eternal: "[I]f superconductivity is caused by interactions between electrons, it is probably due to a somewhat localized tendency for electrons of the same velocity to move together as a unit, which is held together in some way by the inter-electronic forces. In order to stop such a group of electrons, it would be necessary to scatter all of them at once. Such a process would be enormously less probable than one in which electrons are scattered individually by lattice vibrations or other irregularities in the lattice....It would still remain true that a superconducting state which was carrying a large current would have a higher energy than one which carried no current; the current carrying state would then be very long-lived because of the small probability of scattering."[25]

The same idea had been proposed sixteen years earlier, in 1933, by the Soviet theorist Yakov Frenkel: "Let us imagine a crowd of electrons moving in the same way...through the crystal lattice of a metal. Because of the electromagnetic mutual-action of the electrons...the motion of each electron will be affected by an external perturbation...to a much lesser degree than in case it moved alone....Indeed, if an electron is knocked out of the crowd...the resulting change of the total momentum of the whole crowd will not be equal to the individual [momentum] *mv* of this electron, there will be, in addition,...[the] collective term....So long, therefore, as the electrons in a metal move collectively as an organized crowd of sufficiently large size, their motion can remain unaffected by the heat motion of the crystal lattice, the energy and momentum quanta of the heat waves being insufficient to knock out even a single electron."[26]

Frenkel's language is explicitly metaphorical, Bohm's more reserved, but both proposals rely on the basic intuition that electrons must organize to avoid being scattered. For a physicist, this is by no means an obvious assumption, but for anyone associated with labor activism, the advantage of an organized movement over unorganized crowds in their resistance to scattering has the status of an axiom as self-evident as Euclid's first postulate. Both Bohm and Frenkel had personal experience with this socialist axiom. Bohm could not avoid learning this basic lesson on social theory while unionizing at the Radiation Laboratory during the war.[27] Frenkel lived through the Russian revolution in Petrograd, watching workers' dem-

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[25] David Bohm, "Note on a theorem of Bloch concerning possible causes of superconductivity," *PR, 75* (1949), 502-504.

[26] Yakov Frenkel, "On a possible explanation of superconductivity,"*PR*, *43* (1933), 907-912 .

[27] "The collective action was necessary....[An] individual clearly couldn't manage in front

onstrations and revolutionary crowds scattered by, or cutting through, the police lines in very much in the same fashion as, in his description, the crowds of electrons were scattered or unaffected by the lines of ions in the crystal lattice.[28]

A common political background may explain why both came to the same hypothesis independently. Bohm did not know Frenkel's earlier proposal, for otherwise he would have known also that the proposal had been refuted by Hans Bethe and Herbert Fröhlich, who showed that the model of collective magnetic interactions between electrons would not explain superconductivity.[29] No more did Bohm's proposal of 1949 work in superconductivity, at least not immediately. But he already knew—and mentioned at the end of his note, referring to his forthcoming papers—that the same approach would prove fruitful in plasma.

Collective interactions

Although Bohm overlooked Frenkel's old paper in *Physical review*, he paid close attention to current Soviet publications in physics, at least those translated into English in the *Journal of physics* published in Moscow until 1947. There he came across papers that attacked the problem of plasma and many-body theory in a way similar to his and anticipated some of his conclusions. Bohm's student Eugene Gross recalled: "In our first paper on plasma oscillations we had independently discovered the phenomenon of Landau damping....I came upon a copy of the *Journal of physics* containing Landau's solution of the linearized Vlasov equation. Due to wartime dislocations it arrived in Princeton after a delay of a year. I rushed to show it to Dave, who was in the shop constructing a frame for a hi-fi set. He was not at all perturbed at being scooped and simply admired the elegance and incisiveness of Landau's paper."[30] References to the papers by Anatoly Vlasov and Landau of 1945/6 first appeared in Bohm's texts in 1949; probably as a result of that reading, Bohm's language shifted subtly but significantly. Whereas he had conceptualized the behavior of electrons using the unionist notion "organized movement," starting in 1950 he added the word "collective" to his physics vocabulary and named his approach "collective description."

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of all these big corporations or in front of big government organizations. So you had somehow for people to get together in a different way so that they would all really work together and be able to organize properly. But the whole thing had to be organized." (Bohm-Wilkins, 216, also 120).

[28] Kojevnikov (ref. 1), 301-305.

[29] Hans Bethe and Herbert Fröhlich, "Magnetische Wechselwirkung der Metallelektronen. Zur Kritik der Theorie der Supraleitung von Frenkel," *Zetschrift für Physik*, *85* (1933), 389-397.

[30] Eugene P. Gross, "Collective variables in elementary quantum mechanics," in B.J. Hiley and F. David Peat, eds., *Quantum implications: Essays in honour of David Bohm* (Routledge, 1987), 46-65, on 48.

Collectivist terminology, relatively rare in the 1930s, by the 1940s had become common in the language of Soviet physics, in a variety of phrases, meanings, and problems. By collectivism Frenkel, the pioneer of the approach, usually meant shared property. For him, electrons in metals were "collectivized" because they belonged to all the atoms of the solid body together. This notion was the main source of Frenkel's disagreement with the standard "band theory" of metals, which treated electrons as free particles, and of his original approach to the quantum theory of the solid state, which inspired him to introduce the notions of excitons and holes. Frenkel's younger colleague Lev Landau also had serious reservations about the notion of free electrons in solids, but while Frenkel was concerned primarily with the relationship between electrons and ions, Landau paid more attention to the interactions among electrons.[31] The interaction energy appeared to be of the same order of magnitude as the electron's kinetic energy, thus making the main assumption of the band theory physically unjustified. For Landau as for Bohm, the main challenge was to describe the collective interactions and movement in an ensemble of particles.

The main obstacle here, too, was the lack of mathematical methods capable of handling the multi-particle interaction. Admitting in 1936 that a strict solution of the problem seemed impossible at the time, Landau tried several palliative remedies. In a joint paper with his student Isaak Pomeranchuk he treated interaction as a small perturbation added to the free state of electrons. This was obviously insufficient, but at least provided, according to Landau, "the possibility of elucidating the limits of applicability of the existing [band] theory."[32] In search of a more consistent approach, he turned in another paper of 1936 from metals to the similar but simpler case of electrons in plasma, and tried to extend the basic methods of classical kinetic theory from the gas of neutral molecules to the gas of electrically charged ions and electrons. Landau proposed a generalization of Boltzmann's kinetic (transport) equation with a new expression for the collision integral corresponding to the case when particles interact not by strong direct collisions, but via Coulomb forces at long range, thus scattering each other by small angles and with small changes in their velocities. The integral diverged at long distances, but Landau's intuition helped him to make a right guess (later justified mathematically by Bohm) and cut the Coulomb forces at the radius of screening (the Debye radius). The resulting kinetic equation with what later became known as the Landau collision integral allowed him to estimate theoretically the thermal and electrical conductivity of plasma.[33]

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[31] Lev Landau and A. Kompaneets, "The electrical conductivity of metals" (1935), LCP, 803-832, on 804.

[32] Lev Landau and I. Pomerantschuk, "Über die Eigenschaften der Metalle bei sehr niedrigen Temperaturen," *Physikalische Zeitschrift der Sowjet Union, 10* (1936), 649-665; "On the properties of metals at very low temperatures," LCP, 171-183, on 171.

[33] Lev Landau, "Die kinetische Gleichung für den Fall Coulombischer Wechselwirkung," *Physikalische Zeitschrift der Sowjet Union, 10* (1936) 154-164; "The transport equation in the case of Coulomb interactions," LCP, 163-170.

Anatoly Vlasov from Moscow University achieved a real breakthrough in 1938. In "On the vibrational properties of electron gas," Vlasov pointed out an inconsistency: Boltzmann-type kinetic equations with paired collisions work when particles are rare, but in a plasma a sphere with the radius of the electrons' effective interaction included many particles. The collective interaction of electrons produced new effects: thus a fluctuation in the density of particles would not dissipate quickly, as in a normal gas, but oscillate with a characteristic "plasma" frequency

$$\omega_p = \sqrt{4\pi N_0 e^2 / m}\,, \qquad (2)$$

where N_0 is the mean density, e the charge and m the mass of the electron. The existence of plasma oscillations had been demonstrated by Irving Langmuir and Lewi Tonks in the 1920s.[34]

Vlasov replaced the collision integral in Boltzmann's kinetic equation with a term describing the movement of particles in the field jointly produced by them all (the approximation known as the method of the self-consistent field). This provided a complex non-linear system of equations for the density function $f(\boldsymbol{x}, \boldsymbol{v})$ characterizing the distribution of electrons over different values of coordinates and velocities. Vlasov then suggested simplifying the equations by disregarding the relatively rare collisions and considering only small deviations in the density function from the equilibrium Maxwellian distribution f_0. The result was the linearized Vlasov equation:

$$\frac{\partial f}{\partial t} + \mathbf{v}\nabla f = \frac{e}{m}\nabla\varphi\frac{\partial f_0}{\partial \mathrm{v}}\,, \text{ where } \Delta\varphi = -4\pi e\int f d\boldsymbol{v}, \qquad (3)$$

From this simplified equation he could derive the basic features of oscillations in ionized gas, and of electrons in metals: the existence of longitudinal waves with frequencies at and above the plasma frequency and a specific law of dispersion.[35]

After the University returned to Moscow from its war-time evacuation and resumed regular activities in 1943, Vlasov embarked on a more ambitious program based on the fact that his non-linear kinetic equation allowed a variety of non-trivial solutions. Encouraged by the earlier success, he wrote: "In the classical conception of 'paired' collisions the weak existing forces of interaction at 'long' distances (exceeding the mean distance between particles) are disregarded. [This] also disregards the collectivizing effect and together with it a great deal of phenomena….[Taking them into] account reveals totally new dynamic properties of polyatomic systems." Vlasov generalized his set of equations to include not only Coulomb but also other kinds of central forces, even short-range ones, which

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[34] Lewi Tonks and Irving Langmuir, "Oscillations in ionized gases," *PR*, *33* (1929), 195-210.

[35] Anatoly Vlasov, "O vibratsionnykh svoistvakh elektronnogo gaza," *JETP*, *8* (1938), 291-318.

did not satisfy the approximation of the self-consistent field. He aspired to derive much more than oscillations, but "the spontaneous origin of a crystal structure" due to the effect of the collective interactions between atoms, and claimed nothing less than "a change in our conceptions of 'gas,' 'liquid' and 'solid'" by bringing them together with the conception of plasma and thus reconsidering "the problem of the transition from 'micro' to 'macro.'"[36]

Vlasov was punished for his inflated ambition, a few mathematical mistakes, and an unjustified assumption by a severe collective critique, "On the fallacy of the works by A.A. Vlasov on the generalized theory of plasma and the solid state," which came from four high-ranking Soviet theoretical physicists including Landau.[37] The dogmatic and uncompromising tone of the attack reflected the administrative warfare between the U.S.S.R. Academy of Sciences and Moscow State University, at the epicenter of which was the battle for the position of the university chair of theoretical physics, then occupied by Vlasov.[38] He was not given an opportunity to publish a reply in the same journal, controlled by the Academy, and had to send it to the less significant periodical of Moscow University. In a separate paper, Landau used refined mathematical techniques to derive a new solution of the Vlasov equation, which corresponded to the damping of electromagnetic oscillations in plasma owing to collective interaction. As a consequence of this damping, external electromagnetic radiation cannot penetrate deep into plasma.[39]

Meanwhile, in 1946, at a level that bordered on mathematics proper, Nikolai Bogoliubov provided strict justification for both the Vlasov equation and the Landau collision integral as two different approximations in the statistical description of a gas with Coulomb forces.[40] These Soviet accomplishments and the Bohm diffusion equation provided the first treatments of collective phenomena and effects in classical plasma. In Princeton, Bohm set out to develop a more comprehensive, general theory, which he did in a series of papers published from 1948 to 1950 together with graduate student Eugene P. Gross.

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36. Anatoly Vlasov, "On the kinetic theory of an assembly of particles with collective interaction," *JoP, 9* (1945), 25-40, on 25, and "On the theory of the solid state," *JoP, 9* (1945), 130-138, on 130.

37. Vitaly Ginzburg, Lev Landau, Mikhail Leontovich, Vladimir Fock, "O nesostoiatel'nosti rabot A.A. Vlasova po obobshchennoi teorii plazmy i teorii tverdogo tela*," JETP*, *16* (1946), 246-252.

38. G.E. Gorelik, "Fizika universitetskaia i akademicheskaia," *Voprosy istorii estestvoznaniia i tekhniki*, (1990) n. 1, 31-46.

39. Lev Landau, "On the vibration of the electronic plasma," *JoP, 10* (1946), 25-34; L. Landau, "O kolebaniiakh elektronnoi plazmy," *JETP, 16* (1946), 574-586.

40. Nikolai Bogolubov, "Expansions into a series of powers of a small parameter in the theory of statistical equilibrium," *JoP, 10* (1946), 257- 264, "Kinetic equations," *JoP, 10* (1946), 265-274, and *Problemy dinamicheskoi teorii v statisticheskoi fizike* (Moscow, 1946). A.F. Aleksandrov and A.A. Rukhadze, "On the history of fundamental papers on the kinetic plasma theory," *Plasma physics reports, 23* (1997), 442-447; Yu. I. Klimontovich, "Physics of collisionless plasma," *Physics—Uspekhi*, *40* (1997), 21-51.

Bohm was motivated by the desire to understand physically and mathematically how an assembly of free individuals can develop patterns of coordinated, organized behavior. He regarded plasma as an ideal medium for investigating this question. In a liquid, collective motion emerges simply because every particle pushes its immediate neighbors. In plasma, on the contrary, strong collisions between particles are rare, and the organized motion emerges from weak electric interactions that change the motion of each particle only very slightly at a time. Each particle feels subtle but numerous influences from many remote particles simultaneously. The equations of motion in a gas with many-body interaction cannot be solved in a closed form. Yet Bohm, like Vlasov earlier, managed to find a particular class of solutions that corresponded to many particles moving in unison. Thus while theorists could not calculate the behavior of individual particles, they could develop a mathematical theory of the collective, organized movement of the masses. This new class of mathematical solutions was represented by plasma oscillations.

In order to resolve the otherwise hopelessly complicated mathematical problem drastically simplifying steps were required. Instead of the assumption of the gas theory that particles interact one-on-one, plasma theory made use of the fact that electric forces in plasma are weak in comparison to the interactions in a liquid. Bohm was particularly excited that he could start calculations with free particles and see their organized movement develop: "In fact, each particle moves almost freely, except that it experiences a gradual change of velocity caused by the cumulative and simultaneous forces produced by all other particles.…[P]lasma is the only system which is simple enough so that the origin of medium-like behavior can be traced out in detail with the aid of kinetic theory."[41]

Bohm and Gross developed a comprehensive treatment of oscillations in classical (non-quantum) plasma: the origin of organized behavior, their characteristic frequency and, like Vlasov earlier, the dispersion relation,

$$\omega^2 = \omega_p^2 + 3(kT/m)(2\pi/\lambda)^2 \tag{4}$$

(where ω and λ are the wave frequency and length, ω_p characteristic plasma frequency, T the temperature, and k the Boltzmann constant). They calculated the excitation of oscillations from instabilities and their subsequent damping, explained some known effects (the anomalous scattering of fast electrons in plasma, observed by Langmuir), and suggested that their results applied to interstellar plasma. They deduced another important result, the existence of a minimum wavelength—equal to the radius of Debye screening—below which plasma oscillations did not occur. To Bohm, this limit demonstrated that "the motion of a plasma shows only

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[41] David Bohm and Eugene P. Gross, "Theory of plasma oscillations. A. Origin of medium-like behavior," *PR, 75* (1949), 1851-1864, on 1852; David Bohm, "General theory of collective coordinates," in Cécile Dewitt and Philippe Nozieres, eds., *The many body problem—Le problème à N corps* (London, 1959), 401-516, on 401-403.

long-range organization, while locally it is almost indistinguishable from a perfect gas." In other words, plasma particles in their immediate vicinity behaved like free particles, independent of their close neighbors, at the same time coordinating their movements with some other particles at considerable distances, producing collective oscillations on a macroscopic scale.[42]

Direct collisions among neighbors, when they happened, tended to disrupt organized long-range behavior of particles by adding an element of randomness. After such collisions, organizing had to start anew, which meant that plasma oscillations could only set up if direct collisions were rare (the period of oscillation being much smaller than the average time between collisions). At about this stage, a different kind of collision interrupted the development of Bohm's ideas about plasma.

Screening off a foreign body

On April 21, 1949 Bohm received a subpoena to appear before the House Committee on Un-American Activities (HCUA). He had suspected during the war that involvement with leftist activism had prevented his recruitment to Los Alamos and exposed his friend and fellow graduate student Lomanitz to the draft.[43] Bohm subsequently reduced his involvement with political causes to readings and discussions with a few friends, concentrating his main efforts on professional research and teaching, but the earlier war-time episode would continue to haunt him. After the war, when accusations of spying and betrayal were used to undermine popular support for leftist movements, the case of the "communist espionage at the Berkeley Radiation Laboratory" came under HCUA's scrutiny and turned into a high-profile political scandal.

Along with Robert and Charlotte Davis, Lomanitz, Steve Nelson, Frank and Jacquenette Oppenheimer, and Weinberg, Bohm was summoned before HCUA. He discussed a possible course of action with Lomanitz and other friends and colleagues including Albert Einstein. Einstein advised him not to appear before the Committee since participation would have meant agreeing to the legitimacy of the hearings. "You may have to sit for a while," added Einstein, who had witnessed much worse cases of political persecution and could discuss the possibility of a temporary imprisonment somewhat lightly. Bohm was not amused by the possibility. He did possess a tremendous intellectual courage, a rare ability to think independently even against a universal consensus, but he was not a brave man and

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[42] David Bohm and Eugene P. Gross, "Theory of plasma oscillations. B. Excitation and damping of oscillations," *PR, 75* (1949), 1864-1876, "Plasma oscillations as a cause of acceleration of cosmic-ray particles," *PR*, *74* (1948), 624, and, "Effects of plasma boundaries in plasma oscillations," *PR*, *79* (1950), 992-1001.

[43] Russel B. Olwell, "Princeton, David Bohm and the Cold War: A study in McCarthyism" (Junior paper, Department of History, Princeton University, May 1990), 6; Bohm-Wilkins, 223.

FIG. 1 David Bohm in 1949. The original caption on the photograph: “David Bohm, Princeton University physics professor who worked on the wartime development of the atomic bomb, shown outside the House Un-American Activities Committee today where he refused, under oath, to state that he was—or was not—a member of the communist party.” The photograph is damaged in the lower part. *Source:* Library of Congress, New York World-Telegram and Sun Collection; courtesy AIP Emilio Segré Visual Archives.

easily panicked. Throughout his entire life Bohm felt personally insecure, even when no obvious threat existed.[44]

Bohm appeared before the HCUA on May 25 and June 10, 1949, and, like most other academic co-witnesses, invoked the first and the fifth amendments, which guarantee the freedom of speech and protection against self-incrimination. Advised by his attorney Clifford J. Durr, Bohm answered questions related to his academic resumé and research activities, but refused to testify about his own or others' political affiliations or contacts with known communists. He added a statement, however, that he was always completely loyal to the United States and never contemplated or knew of any disloyal acts.[45]

In September 1949, after Truman's announcement of the detected Soviet nuclear test, anti-communist hysteria intensified and centered on leaks of "atomic secrets." HCUA's "Report on Soviet espionage activities in connection with the atomic bomb" accused Joe Weinberg of giving Nelson a secret formula and mentioned Bohm and others as members of the Berkeley communist cell with contacts with Nelson. In 1950, as the outbreak of the Korean War and more serious espionage cases rocked the country, the HCUA intensified its activities and charges of "contempt of Congress" against witnesses who refused to testify became a norm. Bohm had real reasons to worry about his personal safety and freedom.[46]

He was arrested in Princeton on December 4, 1950 by a federal marshal and taken to Trenton to hear eight charges of contempt of Congress. With help from his girlfriend and from Silvan S. Schweber, then a graduate student, Bohm was released on bail. The university administration, however, suspended him from "all teaching and other duties" for the duration of the trial, and ordered that he not appear on campus or lecture to students. Although the Supreme Court ruled in December that use of the fifth amendment was legitimate, the charges against Bohm were not dropped. He was acquitted after the trial on May 31, 1951, and continued to receive a salary from the university until his contract expired in June. Despite the acquittal and the recommendation of the physics department, the anti-communist and possibly anti-Semitic university administration refused to appoint Bohm for another term. The politically tainted physicist did not manage to find other academic appointment in Cold War U.S. and in the fall 1951 emigrated to

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44. Peat (ref. 5), 92.

45. "House of Representatives. Eighty-first Congress. Hearings before the Committee on Un-American Activities. First Session: April 22, 26, May 25, June 10 and 14, 1949" (Hearings regarding communist infiltration of Radiation laboratory and atomic bomb project at the University of California, Berkeley, Calif.—Vol. 1) (Washington, D.C., 1949); DBP: A 117.

46. Olwell (ref. 43); Ellen Schrecker, *No ivory tower: McCarthyism and the universities* (Oxford, 1986); S.S. Schweber, *In the shadow of the bomb: Bethe, Oppenheimer, and the moral responsibility of the scienti*st (Princeton, 2000); Jessica Wang, *American science in an age of anxiety: Scientists, anticommunism, and the Cold War* (Chapel Hill, 1999).

Brazil, where Einstein's and Oppenheimer's letters of recommendation helped him to get a post at the University of São Paulo.[47]

Meanwhile Bohm had continued his research. He recalled that the suspension from teaching was "a big boon, because I had a lot of time to myself. I did a lot of work and I really was able to do my work much better.... Freed from intellectual pressure to conform to a certain line...my mind was able to work more freely."[48] It does appear that external pressure and the status of political outcast made it easier for Bohm to adopt a more radical, at times explicitly non-conformist stance in physics. His work during the two years of legal and political purgatory included a classic textbook on quantum theory, an anti-establishment, anti-Copenhagen, proposal of a causal interpretation in quantum mechanics,[49] and a series of papers applying the new collective description of plasma to the theory of metals.

Dialectics of an individualist collectivist

Bohm later expressed disappointment that, while his mathematical results took on a life of their own in plasma physics, the related larger agenda dropped from view. When, after several years of exile in remote places, he could attend a conference on plasma physics in Europe, he "felt that there was no physics there at all, they were just putting formulae on the [black]board. They were not really interested in questions of what is the collective and what is the individual and things like that....One of the problems that seemed very important [to me] was to get in between the domain of the collective and individual.'[50] In his own research, mathematics, physical intuition, social sensitivity, and philosophical, even metaphysical, concerns intertwined. At heart, Bohm was a metaphysician, inspired by a feeling of the unity, or "wholeness," of the world, and put off by the idea of compartmentalization of different branches of knowledge. His most treasured ideas usually transgressed the disciplinary boundaries of science. Later, in the 1960s, Bohm became disappointed with socialism, and abandoned Marxism for Hegelian dialectics and then the transcendental philosophy of mind and cognition. As the closest associate of the famous Indian guru Jiddu Krishnamurti, Bohm became prob-

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[47] Olwell (ref. 43), 18-25; Peat (ref. 5), 98-100; S.S. Schweber, interview by Alexei Kojevnikov (AIP); Bohm-Wilkins, 341-343; Einstein-Bohm correspondence (DBP: C 11).

[48] David Bohm, interview (ref. 6). "I found that there had been a very subtle repression or oppression going on in the university environment in the sense that, though nobody asked you to do anything in particular, there is a kind of pressure all the time to think in a certain way." (Bohm-Wilkins, 338).

[49] David Bohm, *Quantum theory* (New York, 1951), and "A suggested interpretation of the quantum theory in terms of "hidden" variables, I and II," *PR*, 85 (1952), 166-179, 180-193.

[50] David Bohm, interview by Lillian Hoddeson (1981), AIP, 17-18. One physicist interested in Bohm's larger agenda was Sin-itiro Tomonaga, "Elementary theory of quantum-mechanical collective motion of particles," *Progress of theoretical physics, 13* (1955), 467-481, 482-496.

ably the most distinguished scientist within the broadly defined "new age" movement and the author of many widely popular books on science and human consciousness.

In the early 1950s, Bohm's publications concerned mathematical physics while his general philosophical worldview was Marxist through and through. His Soviet colleagues who developed similar collectivist approaches in physics adhered to political trends increasingly marginal in the Soviet context. Frenkel's background was non-Marxist or anti-Marxist socialism, Tamm was a Menshevik, Landau probably a Trotskyite sympathizer. All had their share of political difficulties, partly resulting from their unorthodox political views, and none joined the Communist Party. All three accepted at least substantial parts of the Marxist social agenda and theory, the so-called historical materialism, and all rejected dialectical materialism especially as applied to science. Similarly, Bohm held beliefs increasingly marginal and unorthodox in his own, American society, but in some aspects—in particular the adherence to dialectical materialist philosophy—they came closer than the views of his Soviet colleagues to what in the Soviet Union was regarded as mainstream.

Explicit references to Marxist philosophy of course do not appear in Bohm's physical papers. Intellectual similarities on the philosophical level, however, especially in his causal interpretation of quantum mechanics, were strong enough to be noticed by some contemporary and later commentators.[51] These common features included an adherence to causality, rationalism, non-reductionism, anti-positivism, the concept of "relative truth," and the ultimate reality of matter. Whether he read Lenin's famous dictum that "the electron is as inexhaustible as the atom" in *Materialism and empiriocriticism* during his Princeton time, as reported, or in some other publication, the often quoted statement was in perfect accord with Bohm's "hidden variables" theory. According to it, whatever at the level of atoms and electrons appeared as strange, non-causal behavior, could be explained at a deeper level by a perfectly causal mechanism involving even more microscopic constituents.[52]

Bohm's thought had a Leninist, dialectico-materialist cast. He wrote to a friend from Brazil:[53]

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[51] Peat (ref. 5), 138; Pauli to Marcus Fierz, 6 Jan 1952; Evry Schatzman, "Physique quantique et realité," *La Pensée* (1952), n. 42-43, 107-122; Hans Freistadt, "The crisis in physics," *Science and society, 17* (1953), 211-237.

[52] This paper does not attempt to give an account of Bohm's "hidden variables" theory and the related causal interpretation of quantum mechanics, which has been the subject of serious discussion. For a details philosophical analysis of Bohm's interpretation (without its political aspects) and for further references see James T. Cushing, Arthur Fine and Sheldon Goldstein, eds., *Bohmian mechanics and quantum theory: An appraisal* (Boston, 1996) and James T. Cushing, *Quantum mechanics: Historical contingency and the Copenhagen hegemony* (Chicago, 1994).

[53] Bohm to Hanna Loewy [1951 or early 1952] (DBP: C39); also Bohm to Melba Phillips,

> I have been doing more work on my theory, and have shown that there seems to be a connection between [my works on the interpretation of] quantum theory and plasma theory....Briefly, I am led to the notion that all space is filled with a substratum…made up of particles millions [of] times smaller than an electron or proton, and that electrons and protons, etc. are structures in this substratum….Of course, the substratum should be only "relatively absolute"….The so-called "particles" of any given level are made up of structures in the "particles" of the lower level, etc. ad infinitum. I feel that both the qualitative nature of these particles and the number in existence can be collectively conditioned. Thus, not only is the collective behavior determined by the infinitely complex individuals…, but the individuals are themselves determined in part by the collective in which they are participating. Because of the infinity of levels, you cannot say that there are any ultimate "individuals," which are "fundamental" in the sense that their character in unalterable, and their existence eternal. At any level, any particular form of matter can always come into existence and go out of existence as a result of a transformation in the components existing at a lower level, but only matter as a whole, in its infinity of properties and possibilities, is eternal.

Of all this metaphysics, Bohm's published papers on plasma include an attempt to approach dialectically the relationship between collective and individual.[54] Bohm learned the Marxist dialectical principle of the "unity of opposites" in one package with Bohr's idea of quantum complementarity in Berkeley from Joe Weinberg, for whom the two concepts were essentially identical. The dialectical idea made a strong impression on Bohm, but for him "the major question was the individual and the society" rather than the dialectics of waves and particles.[55] He subsequently rejected Bohr's complementarity in quantum physics, but dialectics and the unity of opposites remained among his deepest beliefs and even survived his disillusionment with Marxism. This strong appeal may have been grounded in the basic internal contradiction of his personality: an intense (but not really fulfilled) desire to be part of a collective combined with an even stronger imperative to think independently. Another factor was the basic contradiction of the surrounding society as he perceived it.

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22 Oct 1951, 15 Jan [1952], and 13 Oct 1953 (DBP: C46, C48).

[54] Connections between Bohm's causal interpretation of quantum mechanics and his political views have been pointed out by Andrew Cross, "The crisis in physics: Dialectical materialism and quantum theory," *Social studies of science, 21* (1991), 735-759; Olival Freire Jr., Michel Paty, and Alberto Luiz da Rocha Barros, "Physique quantique et causalité selon Bohm—Analyse d'un cas d'accueil defavorable," XX International Congress of the History of Science, Liège (1997); Russell Olwell, "Physical isolation and marginalization in physics: David Bohm's Cold War exile," *Isis*, *90* (1999), 738-756; Shawn Mullet, "Political science: The red scare as the hidden variable in the Bohmian interpretation of quantum theory" (Senior thesis, University of Texas at Austin, 1999).

[55] Bohm-Wilkins, 238. "The unity of opposites excited me….[T]hings which seemed opposite were actually underlying unity and that out of them would emerge creatively new synthesis….I thought a lot about the unity of opposites and to some extent it inspired some of my work in plasmas." (Bohm-Wilkins, 213-214, also on 256.)

At stake in the propaganda battles about communism in general, and in some personal attacks on Bohm in particular, were different conceptions of freedom. Communists, declared Princeton university president Harold W. Dodds, surrendered "their rights as persons." They submitted themselves to "slavery of bodies, minds and souls....They are not just radicals. They are part of an international conspiracy. The Communist doctrine denies academic freedom. Its followers cannot be honest." Dobbs personally decided to terminate Bohm's appointment at Princeton.[56] In Bohm's eyes, however, self-appointed defenders of freedom like Dobbs not only sacrificed academic freedom, but acted as the ultimate conformists, "[p]eople...too frightened to do other than try to conform. The people who talked about individualism and freedom were not individualistic. They were the most collective people I knew. They had no thoughts of their own. They were afraid to have them. They didn't want anybody to have them."[57]

Having experienced anti-communist persecution and arrest, Bohm became increasingly aware of the other side of the problem of collective action, the danger of excessive conformity. His thinking included not only the major problem of sociology—how stable and conformist patterns of behavior emerge in a society composed of individuals who are free, or consider themselves free—but also the additional challenge, with personal implications, of how to maintain personal freedom in a conformist environment. His theories in physics and in politics accordingly became more sophisticated. Once again, plasma seemed to offer a solution to this reformulated dilemma of freedom. If initially Bohm was primarily motivated to explain mathematically how free particles create a collective movement, starting around 1950 he worked to construct mathematical possibilities for a state of freedom out of the collective interaction of particles. The free solutions that he found represented not the original electrons, but new "collective individuals," or "quasi-particles."

Mathematical principles of collective freedom

The mainstream approach to the theory of metals of the 1950s, the band theory, considered electrons in metals as essentially free particles. Bohm hoped to create a more realistic picture of the metallic state by describing interactions among electrons as he had done in plasma. The density of electrons in metals is much higher than in ionized gas, and quantum effects become essential. Bohm had dealt with a plasma of interacting classical particles; now he had to consider a highly degenerate quantum gas, that is, he had to develop a theory of quantum plasma. Bohm pursued this work with another graduate student, David Pines. They proposed a "new approach to the treatment of the interaction in a collection of electrons,...the collective description." They completed their first preliminary note and the first

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[56] Olwell (ref. 7), 744; William Bradford Huie, "Who gave Russia the a-bomb?" *The American mercury* (1951), 413-421, on 413.
[57] Bohm-Wilkins, 173-174, also on 90, 116.

part of a detailed study during the year Bohm was under the HCUA's scrutiny; the second part while he was barred from teaching; and the third part by correspondence after Bohm had left the U.S.; Pines published part four alone.[58]

Aiming to translate the treatment of classical plasma into quantum language, Bohm and Pines needed to rewrite their formulas in the Hamiltonian formalism and find a canonical transformation to a new set of variables corresponding to organized oscillations. They succeeded in overcoming most mathematical difficulties and found expressions for new sets of what they called "collective variables" and "individual particle variables." Rewritten in these variables, the total Hamiltonian effectively separated into three parts: the kinetic energy of particles, the energy of collective oscillations (long-range interactions), and the particles' short-range interaction energy via an electrical potential screened at the Debye radius.

The results include the first mathematical account of many-body interactions of electrons in metals, a demonstration of the limitations of the existing individual electron theories; the conditions under which the individual-electron theory held, and an explanation why, despite its seemingly unnatural assumptions (disregarding the interactions between electrons, etc.), the agreement between the calculations of the old theory and experimental measurements was in many cases quite good. Bohm and Pines also explained why previous attempts by John Bardeen at improving the band theory by adding a Coulomb interaction calculated with the help of perturbation methods worsened the gap between experiment and theory, while, on the contrary, similar calculations with a screened potential—for example Landau's—produced encouraging results.

For Bohm, the investigation had an even larger significance, bearing on the general problem of freedom. In his student days, he was puzzled how a human being constructed from the deterministically moving atoms of classical mechanics can nevertheless be free.[59] With a very different kind of physics, he would do something vaguely similar in his plasma theory of metals of 1951: construct freedom not as a straightforward, natural, and simple condition, but as a complex, emerging state. Metallic electrons interacting by Coulomb forces would strongly scatter each other and thus reduce their mean free path inside metals much below what experiment suggested. Bohm's collectivist description ruled this out: owing

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[58] David Bohm and David Pines, "Screening of electronic interactions in a metal," *PR*, *80* (1950), 903-904, "A collective description of electron interactions. I. Magnetic interactions," *PR*, *82* (1951), 625-634, "A collective description of electron interactions: II. Collective *vs* individual particle aspects of the interactions," *PR, 85* (1952), 338-353, on 338-339, and "A collective description of electron interactions: III. Coulomb interactions in a degenerate electron gas," *PR, 92* (1953), 609-625; David Pines, "A collective description of electron interactions: IV. Electron interaction in metals," *PR, 92* (1953), 625-636. Lillian Hoddeson, Helmut Schubert, Steve J. Heims, and Gordon Baym, "Collective phenomena," in *Out of the crystal maze: Chapters from the history of solid-state physics* (Oxford 1992), 489-616, on 534-538.

[59] Bohm-Wilkins, 151-152.

to their collective organization and interactions, electrons became effectively freer than they would have been individually, and traveled long distances inside the metal without being scattered: "[A]ll this prediction of tremendous electron scattering was wrong....[The organization in plasma] affected the individual particle's interest and the more organized it became, the freer became the individual particles. Whereas, previously, the individual particles would have messed up with each other without that organization."[60]

As in his work with Gross on classical plasma, Bohm's work with Pines on electrons in metals showed that "for phenomena involving distances greater than the Debye length, the system behaves collectively; for distances shorter than this length, it may be treated as a collection of approximately free individual particles, whose interactions may be described in terms of two-body collisions." "Our main conclusion is that neither the collective description nor the individual particles description of the electron gas is by itself entirely adequate. For not only is each description needed in its appropriate region, but also the interaction between collective and individual aspects determines many important properties of the system. It is just this synthesis of individual and collective aspects that makes the electron gas such an exceptionally interesting medium."[61]

The collective part of the electrons' movement again was represented by long-range oscillations. The density of electrons in metals was typically 10^{10} times higher than that in the arc plasma, with a corresponding wavelength not in the region of microwaves (10^{-3} cm), but of the order 10^{-9} cm. Under normal or low temperatures, such oscillations would be negligible, but they could be excited in a metal by a fast moving electron, just as a supersonic projectile generates a shock wave in the air, or superfast electrons generate Cherenkov radiation in a medium.[62] Conyers Herring of Bell Labs, who had an encyclopedic knowledge of the literature in the field, pointed out to Bohm and Pines that their theoretical prediction already had an experimental justification of sorts, in experiments on the bombardment of thin metallic films by fast electrons performed in Nazi Germany, but published only after the war.[63] The quantum of these oscillations was a close analog of the quantum of lattice oscillations, the phonon, and in 1956 Pines introduced the name "plasmon" for it.[64]

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60. Bohm-Wilkins, 316-321, on 321.
61. Pines and Bohm II (ref. 58), *2*, 338-339.
62. Bohm and Pines III (ref. 58); Pines IV (ref. 58).
63. Gerhard Ruthemann, "Diskrete Energieverluste mittelschneller Elektronen beim Durchgang durch dünne Folien," *Annalen der Physik*, *2* (1948), 113-134, and "Elektronenbremsung an Röntgenniveaus," *Annalen der Physik*, *2* (1948), 135-146; W. Lang, "Geschwindigkeitsverluste mittelschneller Elektronen beim Durchgang durch dünne Metallfolien," *Optik*, *3* (1948), 233-246.
64. David Pines, "Collective energy losses in solids," *Reviews of modern physics*, *28* (1956) 184-198, and "The collective description of particle interactions: From plasmas to the helium liquids," in Hiley and Peat (ref. 30), 66-84.

The remaining part of the Hamiltonian contained individual particles interacting via a short-range screened interaction. These were electrons carrying along a screening "cloud" that repelled other electrons, making direct collisions between them less frequent. The effective increase in the mean free path justified treating the resulting object as a "free" particle. In addition, the object—an analog of the renormalized electron in Schwinger's quantum electrodynamics—had novel properties such as a new, effective mass. In the language of later physics, it belonged to the class of quasiparticles; Bohm called it an "effective individual particle." A couple of years later he wrote: "We have thus split the plasma into two parts, namely the collective oscillations and a set of point particles screened by clouds having these points as centers. The combination of a point particle with its cloud may be regarded as a new kind of effective particle with finite radius, and with a zero net charge, but with short range mutual electrical interaction. Now, insofar as short range effects are concerned, this effective particle will be a more nearly independent unit than was the original particle.…It must be stressed, however, that insofar as certain kinds of long-range effects are concerned, these effective particles are not completely free of each other."[65]

The effective particles were not completely free because collective movements and variables used some of the system's degrees of freedom. If the total number of original electrons was N and the number of collective degrees of freedom S, the effective individual particles had only $3N - S$ degrees of freedom. However, a mathematical transformation to $3N - S$ coordinate variables would give a system of completely free and independent objects. Bohm described these new mathematical constructs as "pulses" in plasma. Such a pulse did not consist of a certain set of particles (electrons in them were being constantly replaced by others), but the structure of the pulse remained stable and particle-like. Bohm called such pulses "collective individual particles" and explained the concept with the help of yet another socio-political metaphor: "To illustrate the meaning of collective individual particles, one may make an analogy to an organization of individuals. First of all, these may have a mass collective effect, in which each individual makes a small contribution, while all of the contributions add up to produce a large net result. This is analogous to the plasma oscillations. But then the organization may have officers, or committees, who are always individuals, or made up of several individuals. But with the passage of time, different individuals can fill the same office, insofar as the functions of this office are indifferent to the special characteristics of the individuals concerned. Nevertheless, the office retains a certain permanence, and can be regarded as a collective individual." Bohm added that in some real (communist?) organizations, "the same man might remain in office indefinitely," but in the collective organization in plasma, rotation takes place.[66]

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[65] David Bohm, "General theory of collective coordinates," in (ref. 41), 401-516, on 436-437.

[66] Ibid., 492.

The collective individual particle may not have achieved widespread recognition, but the other main results that Bohm delivered in his series of papers still lie at the very foundations of plasma physics. Most of the later development in the field, however, occurred without Bohm's personal participation. His emigration to Brazil and his iconoclastic 1952 proposal of a causal interpretation of quantum mechanics, removed him from the scene. Pines remained the main representative of their collective approach in the U.S. He developed the new mathematical methods further and contributed in a crucial way to the propagation and recognition of the collective approach, especially in the theory of metals. He found a new patron in John Bardeen and worked for several years in Bardeen's group at the University of Illinois, which produced a rhetorical adaptation of the approach to a new, politically conservative environment. Thus in his major review article of 1955 Pines felt obliged to stress that since the collective approach justified the limited validity of the old free-electron model in the solid state, "an apparently radical movement turns out to be essentially conservative at its core."[67]

Radical or not, collectivist approaches were spreading far and wide in the American physics community during the 1950s. The Bohm-Gross theory succeeded in plasma physics, as the Bohm-Pines approach transformed the theory of metals. Other similarly important advances, such as Ben Mottelson's collective theory of the nucleus, may have had an independent motivation. But the greatest influence apparently came from Soviet physics, especially the Landau school, in particular through Landau's popular theories of superfluidity and the Fermi liquid. Most Soviet research in those years appeared only in Russian; not until 1955 did the American Institute of Physics start translating *JETP*, the main Soviet physical journal, into English. The Bell Labs group, however, was kept informed by the encyclopedic Conyers Herring, who read Russian, and some translations of Soviet scientific papers were commissioned and made available to interested academics by the CIA and other special agencies.[68]

While still in Princeton, Bohm began another project with graduate student Tor Staver. They intended to extend the collective description to the problem of superconductivity by including the interaction between the electron plasma and the vibrations of the lattice.[69] Unfortunately, Staver died in a skiing accident before he finished his thesis. Bohm did not continue the project on superconductivity after his move to Brazil, although he did some occasional work on the collective approach and many-body problems through the 1960s.[70] He devoted his main ef-

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[67] David Pines, "Electron interaction in metals," in Frederick Seitz and David Turnbull, eds., *Solid state physics: Advances in research and applications*, Vol. 1 (New York, 1955), 367-450, on 376.

[68] Philip Anderson and Conyers Herring, interviews by Alexei Kojevnikov (AIP).

[69] David Bohm and Tor Staver, "Application of collective treatment of electron and ion vibration to theories of conductivity and superconductivity," *PR, 84* (1951), 836-837.

[70] David Bohm, K. Huang, and David Pines, "Role of subsidiary conditions in collective description of electron interaction," *PR, 107* (1957), 71-80; David Bohm and Gideon Carmi, "Separation of motions of many-body systems into dynamically independent parts by pro-

forts after 1952 to developing the hidden-variable theory of quantum mechanics and related philosophical issues. The subsequent development of the theory of superconductivity, however, came about through an interaction and competition between collective and individual-particle approaches.[71]

As collectivist approaches proved their effectiveness and became mainstream methods in several branches of physics, including low temperature and nuclear research, they were developed further by physicists who were neither socialists nor even leftists. Pines, for example, does not seem to have shared Bohm's socialist sympathies. However, he understood that the approach appeared dangerously "radical" and thus required damage control. Pines continued using collectivist mathematics and terminology in his subsequent research, but made sure to avoid any allusions at the possible political means of the language.

Some other physicists, for example Bardeen, appreciated the physical results and mathematical apparatus delivered by Bohm's approach, but did not like the politics behind it. Many more either regarded any kind of politics as inappropriate in physics or were not sensitive enough to hear the political undertones. Nonetheless, the methods continued to be used and developed ever more widely; collectivist concepts came to stay in physics while the original connection with political ideas dropped away, or rather became invisible. Most condensed matter physicists today use collectivist terms in their professional language apparently without thinking that these words may have other meanings as well.

Conclusion: Physics and socialism

In Brazil, Bohm initially enjoyed being "away from people who prevent the free use of one's imagination," but soon isolation, health problems caused by local food, and disappointment with the department made him consider moving. He did not expect, and neither did Einstein, that the political climate in the U.S. would allow his return in the near future. Travel to any other country, however, was made difficult by the confiscation of his passport in December 1951, shortly after his arrival in Brazil. In 1954, in order to be able to accept a position at the Technion in Israel, Bohm took out a Brazilian passport, effectively losing his U.S. citizenship. In 1957 he moved from Israel to England, first to Bristol and, in 1961, to Birkbeck College, University of London, where he held the chair of theoretical physics until his retirement in 1986.[72]

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jection onto equilibrium varieties in phase space, I and II," *PR, 133A* (1964), 319-350; David Bohm and B. Salt, "Collective treatment of liquid helium," manuscript rejected by *PR* in 1966 (DBP: B5-B9).

71. Edward P. Jurkowitz (ref. 24); Hoddeson, et al. (ref. 58).

72. Bohm to Melba Phillips [Dec 1951] and 15 Jan [1952] (DBP: C46); Bohm to Lili Kahler [1952] (DBP: C28); Bohm-Einstein correspondence (DBP: C 11-14). Bohm retrieved his American citizenship in 1986 (DBP: A 123).

In Israel and later in England, Bohm continued his work on the foundations and interpretation of quantum mechanics, which led to further landmark accomplishments, in particular the Aharonov-Bohm effect and the elucidation of nonlocality as a key feature of quantum theory. Nonetheless, his interpretation appeared subversive to the mentality of Cold War physics and was largely ignored by the establishment or rejected without discussion. By 1956 Bohm realized that Soviet physicists, too, had become intellectually conservative, making him feel "discouraged about the state of the world." Khrushchev's revelations of Stalin's crimes caused Bohm to rethink his political position. He became convinced that the Soviet leadership was "compromising the socialist goal by its 'means' " and that "new theories [were] needed for the new situation."[73] He gradually abandoned Marxism and moved towards the "new age" worldview. What remained as his most persistent attitude, and what at the end of his life he said cherished above most other things, was the ability to think differently from others.

Bohm's theories described in this paper constitute only one of an extended family of collectivist approaches and models, mostly dating from the middle of the 20th century, that now belong to core methods in the theories of solids, liquids, plasmas, atomic nuclei, and virtually all other physical systems with many-body interactions. The important ingredients in these approaches are not only quasiparticles, the initial object of this inquiry, just as Bohm's program in plasma physics delivered much more than the plasmon. The variety and the range of collectivist methods also far exceeded expectations at the outset. In all cases studied—Frenkel's collectivized electrons, holes, and excitons, Tamm's phonon, Landau's superfluidity and "collective excitations," Bohm's collective-individual plasma, and Edmund Stoner's collective ferromagnetism—collectivism as a concept and corresponding political metaphors played a crucial role at least during the initial stages of model building. The main controversy these innovations stimulated was rooted in disagreements regarding the general problem of freedom.[74]

Not only socialists and believers in collectivism judged that the band theory of "free" electrons in metals suffered from not considering interactions between electrons. But having socialist beliefs proved to be an advantage, providing an additional strong reason to look for better models, an appropriate ground to build upon, and a vision that supplied intuitions. Without the special philosophical, linguistic, and metaphorical resources associated with the concept of collectivism it would have been harder for physicists to conceptualize the states of particles more complex than "free" and "bound" and to invent mathematical methods capable of treating such states and collective interactions. It thus appears that we deal here with a

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73. Bohm to Melba Phillips, 18 Mar 1956 and [1956] (DBP: C49).

74. Some additional cases are listed in Kojevnikov (ref. 1), on 330-331. A comparable case, but dealing with the concept of "democracy" in elementary particle physics, is discussed in David Kaiser, "Nuclear democracy: Political engagement, pedagogical reform, and particle physics in postwar America," *Isis, 93* (2002), 229-268.

fundamental contribution of socialist thought to the development of mathematical and theoretical physics during the last century.

Some aspects of how this contribution came about warrant special attention. Although it had a core Soviet component, the process was not limited to one country or social context; it cannot be seen as merely "grounded in local practices," as is often preferred these days in science studies. It included many comparable but independent cases, and a variety of socialist traditions and ways of thought, both mainstream and marginal. The concept of collectivism, though hardly a topic of open philosophical debate in science, made a greater conceptual impact than other aspects of socialist ideology with claims on scientific knowledge, for example, dialectical materialism. This impact can be traced to the very mathematical core of "hard" science. The main vehicle that enabled such a fundamental contribution of political thought to exact science appears to have been linguistic—the transfer of vocabulary and metaphors (along with associated intuitions and meanings) from one branch of language to another. Last but not least, the successful propagation of socialist concepts in physics depended upon their evolution or translation into politically more neutral forms, which helped to avoid an openly politicized controversy and make easier their acceptance by wider circles of scientists, far beyond the core group of socialists and leftists. The effective invisibility so achieved suggests that more cases of this sort will be found, and not only in science. It might prove to be a widespread common form of socialist legacy.

ALEXEI KOJEVNIKOV

David Bohm and collective movement

ABSTRACT:

Collectivist philosophy inspired David Bohm's research program in physics in the late 1940s and early 1950s, which laid foundations for the modern theory of plasma and for a new stage in the development of the quantum theory of metals. Bohm saw electrons in plasma and in metals as capable of combining collective action with individual freedom, a combination that he pursued in his personal and political life. Mathematical models of such complex states of freedom, developed by Bohm and other socialist-minded physicists (Yakov Frenkel, Lev Landau, Igor Tamm), transformed the physics of condensed matter and led to the introduction of a new fundamental physical concept, collective excitations or quasiparticles. Together, these contributions illustrate the impact of socialist thought on the development of physics during the last century.
