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Convergence in Cold War Physics: Coinventing the Maser in the Postwar Soviet Union*

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Summary: At the height of the Cold War, in the 1950s, the process of parallel invention of masers and lasers took place on the opposing sides of the Iron Curtain. While the American part of the story has been investigated by historians in much penetrating detail, comparable Soviet developments were described more superficially. This study aims at, to some extent, repairing this discrepancy by analyzing the Soviet path towards the maser from a comparative angle. It identifies, on the one hand, significant differences between the two projects regarding their heuristics, the relationship between theory and experiment, grounding in different academic cultures, and the resulting conceptualization of the maser principle. At the same time, the case also illustrates more fundamental transformations in the practices of postwar research that can be characterized as a convergence between the Soviet and the American science of the period.

Keywords: maser, quantum electronics, Cold War physics, Soviet science, militarization of physics, comparative studies, Alexander Prokhorov, Nikolai Basov, Charles Townes

By the mid-1950s, after several years of restrictions on contacts with Western scientists, Soviet physicists gradually resumed their participation in international conferences and began to restore communications with foreign colleagues.[1] Alexander Mikhailovich Prokhorov (1916–2002) travelled to his first conference outside the communist part of the world in the spring of 1955, to the meeting of

[1] Ivanov 2002.

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the Faraday Society in England where he gave a presentation on the "Theory of the Molecular Generator." Prokhorov's proposal of a fundamentally new kind of electronic device came as a big surprise to another participant at the conference, the American physicist Charles H. Townes (1915–2015), who had been independently working on the same kind of generator since 1951. Townes and collaborators called their apparatus the MASER (abbreviated from Microwave Amplification by Stimulated Emission of Radiation). Townes later described the episode as a "revealing," "eye-opener" encounter, for he had not known about the rival Soviet project. Theoretically, Townes had much to learn from Prokhorov's approach, but on the experimental side, the American team was definitely ahead. "After the presentation," Townes recalled, "I got up and said, Well, that is very interesting, and we have one of these [generators already] working."[2]

The fact that essentially the same device was being invented in parallel on both sides of the Iron Curtain at the height of the Cold War, despite high barriers for personal communications and scientific exchanges, could surprise not only participants at the 1955 conference, but also many later Science and Technology Studies scholars who imbibed Harry Collins' famous mantra that "no scientist succeeded in building a laser by using only information found in published or other written sources."[3] The Townes-Prokhorov episode, however, was not completely exceptional or unprecedented, but quite symptomatic of a general trend. Physics in the United States and in the Soviet Union often evolved along similar lines during that period, a fact acknowledged by the Nobel Committee's decision to award its 1964 prize in physics jointly to Townes, Prokhorov, and Nikolai Gennadievich Basov (1922–2001) "for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle." In this paper, we will analyze the Soviet physicists' path towards the co-invention of the maser and argue that, despite political divisions and cultural differences, in this early period of the Cold War, the practice of physics in the Soviet Union and in North America underwent important restructuring that made them more similar rather than distinct.

The logic of the Cold War conflict and Cold War historiography has typically directed scholars to focus primarily on differences in order to emphasize oppositions and contrasts between the two great powers and ideologies. Much less attention has been paid to the other side of the story: that intense competition also encouraged mutual observation and many important if unadvertised imitations, adaptations, and borrowings on either side. Those who wrote about this trend, from Jan Tinbergen to John Kenneth Galbraith, to Andrei Sakharov, usually characterized the resulting structural similarities as "convergence" between the two systems of modern industrial society.[4] For the purposes of this study, it is important to emphasize that the convergence theory was, first of all, a description of the then existing trends which became particularly powerful during the 1960s, and

[2] Townes 1999, on 76–78.
[3] Collins 1992, on 55.
[4] Tinbergen 1961. Already the first broad sociological studies on Soviet society promoted by American military agencies concluded that "the Soviet Union was a stable industrial society, in important ways not so different from the United States." See: Engerman 2010, on 399.

only secondarily attempted to extrapolate the ongoing momentum into long-term predictions for the future. Those converging trends embraced, besides economics, many other aspects of social and political life. For example, Soviet values and influences affected such important developments in the West as planning and the regulation of capitalist markets, support for women's equality and legalization of abortion, acceptance of decolonization and racial equality, multiculturalism and affirmative action, and greatly expanded access to higher education and universal healthcare.

Cold War science was not exempt; on the contrary, the process of convergence was much easier for it, because both the American and Soviet systems, despite their ideological oppositions on other fronts, shared a similar embrace of scientistic and technocratic values. Both of them during that period granted science and technology unprecedented prestige and government support, especially due to the 1957 launch of Sputnik and the resulting space race.[5] As we will see, converging trends in Soviet and American science at the height of the Cold War included not only intellectual and technological developments, but also institutional and structural similarities.

The growth of institutional infrastructure for research and development represented one such common trend beneath the guise of ideologically opposite labels. The characteristically Soviet model of science became established in the mid-1930s. Sergei Vavilov, the President of the USSR Academy of Sciences from 1945 to 1951, described its key features, including generous government funding, emphasis on practically useful research, and a structural organization in which privileged research institutes with large, multidisciplinary teams of scientists, engineers and technicians worked together on the pursuit of goal-oriented research, combining basic science with technological inventions.[6] Initially, the Soviet research model came about through a compromise between the Bolshevik government and non-party scientists on the basis of a shared understanding that science and technology were the key tools necessary to transform the Soviet Union into a modern state.[7] In the United States, federal funding for research and development also gradually became an acceptable practice during the New Deal. World War II and the Cold War further transformed American science in the direction of what, from Vavilov's perspective, resembled the socialist model of science, but what in the United States became known under a more neutral term, "big science." Not unlike Soviet scientists, many American researchers also became accustomed to state-sponsored and goal-oriented projects, the symbiosis between science and engineering, collective and multidisciplinary work, and complex hierarchies inside huge federal, military-funded laboratories, with excessive bureaucratic controls and secrecy.[8]

The atomic bomb and the Cold War brought about the deep militarization of science in both countries, which reached its apogee after 1950. American and Soviet physicists were recruited, or enlisted themselves, into massive efforts to

[5] Kojevnikov 2008; Wolfe 2012.
[6] Vavilov 1948.
[7] Kojevnikov 2013.
[8] Wolfe 2012; Kevles 1990.

strengthen the military capabilities of their conflicting states. The consequences of this symbiosis between research and military establishments has attracted much analysis and debate within the history of science over the last forty years. Paul Forman, in particular, has argued that the material culture and ethos inherited from wartime projects and the scope of federal support for physics through military channels thoroughly transformed the practice of American physics as a discipline. From the end of World War II through the 1960s, they helped determine what knowledge quests were considered important, achievable, and prioritized. Forman's analysis also demonstrated the deep structural effects of military patronage on fields and topics that remained nominally civilian and unclassified, such as microwave spectroscopy and quantum electronics (the field that would eventually encompass all maser- and laser-related research). Even when researchers such as Townes still believed in and proclaimed themselves supporters of the ideology of pure science, their projects, such as masers or atomic clocks, were deemed strategically relevant for national defense, relied on military funding, and often constituted an unclassified tip of the much larger defense-oriented project pursued with the same equipment within the walls of the same laboratory.[9]

Ian Hacking thus called the laser "a remarkable gift" from the Department of Defense,[10] a phrase that summarizes well the role of the military in the development of quantum electronics. Doubtlessly, the military funding, knowledge, and technology created in the effort to develop radar during the war, the skills and expertise acquired by physicists from military projects, and postwar programs devised by military agencies were crucial to the invention of the maser in the United States. Hacking's remark, however, leaves unacknowledged the work of scientists in Europe and the Soviet Union who contributed to this invention. In her book *The Laser in America*, Joan Bromberg admitted that "even the historian who looks at the American work alone sees continually the impact of developments in Europe and the Soviet Union."[11] Several other authors have gone somewhat further in integrating specific contributions of Soviet scientists into the general history of masers and lasers, but the general institutional context, practice and research culture from which the Soviet works emerged, and in particular its relationship with classified military projects and funding, have not yet been properly studied in the existing literature.[12]

In this paper, we aim to analyze the coinvention of the maser in the Soviet Union while drawing comparisons based upon the existing major histories of the American developments. While we cannot cover the general development of quantum electronics in the USSR within the scope of one short article, it is possible to focus on the key local laboratory that was responsible for the initial invention of the Soviet maser and compare its characteristic features with the American analog. We will try to reveal the factors, constraints, and opportunities that were at play in the Soviet context and allowed Prokhorov and Basov to achieve their

9 Forman 1987; Forman 1992; Forman 1995; Forman 1996. For a recent review of Cold War physics, see: Oreskes 2014.
10 Hacking 1999, on 179.
11 Bromberg 1991, on XII.
12 Dunskaia 1974; Bertolotti 2005; Hecht 2005; Vakulenko 2006. For a comparison between East and West Germany, see: Albrecht 2019.

breakthrough results. Our goal is to develop an analysis capable of capturing and characterizing both similarities and differences and addressing the question of what happened when scientists formed in strikingly different scientific and political cultures began to ask similar questions and aim at similar goals. We will see that although Soviet and American scientists conceived of the same kind of device, they did not have the same understanding of its functioning, due to their grounding in different academic cultures and research traditions.

The first section of this article describes the research tradition of the School of Oscillations, a scientific school established in the USSR before World War II to which Prokhorov belonged and on whose conceptual methods he relied in his work on the maser. Section 2 addresses the militarization of Soviet science that started in the late 1930s and extended much further during the early Cold War, its impact on the careers of physicists of Prokhorov's and Basov's generations, and their research goals. Section 3 discusses how the strategy of following the American example of building the atomic bomb, summarized in the Soviet slogan "to catch up and to surpass," also expanded beyond nuclear physics and was adopted by researchers in other fields, including Prokhorov's group and its focus on microwave spectroscopy. Section 4 finally arrives at the invention of the maser, providing a comparison of the Soviet and American approaches to the invention and their respective conceptualizations of the device. In the conclusion, we summarize the similarities and differences of the American and Soviet paths to masers and reflect on what lessons this comparative case study offers to the general conceptual problems of militarization and convergence in Cold War science.

1. The School of Oscillations

After completing his studies of physics at Leningrad State University, in the summer of 1939 Alexander Prokhorov became a graduate student (*aspirant*) at the Lebedev Institute of Physics, also known as FIAN, the Russian acronym for the Physical Institute of the Academy of Sciences. FIAN had recently transferred to Moscow, together with the headquarters of the USSR Academy of Sciences, and was developed by its director Sergei Vavilov into a major hub of Soviet physics. Many of its leading researchers belonged to the so-called Mandelstam school, or School of Oscillations, formed around and under the intellectual tutelage of the Moscow University professor Leonid Isaakovich Mandelstam (1879–1944). Mandelstam and his lifelong collaborator Nikolai Dmitrievich Papaleksi developed an original approach to many fundamental physical problems based on the general concept of oscillations, especially nonlinear ones, that underlie a wide range of natural processes in various, otherwise unrelated, fields of physics. Prokhorov, and later Basov, both received their professional training in FIAN's Laboratory of Oscillations, where they learned the basic methodology and conceptual approaches of the Mandelstam school.[13]

The origins of the oscillatory approach to physics can be traced back to the work of the German physicist Karl Ferdinand Braun, one of the pioneers of radio and a winner of the physics Nobel prize of 1909 for his contributions to wireless

[13] Pechenkin 2019.

telegraphy. Mandelstam and Papaleksi studied and collaborated with Braun in Strasbourg and Berlin and acquired their expertise and early academic recognition in the field of radio technology. They both returned to Russia in 1914, with the outbreak of World War I, and continued their research on radio technology there. The war, the Revolution, and the Civil War interrupted most of the existing foreign contacts for Russian scientists. Mandelstam and Papaleksi now relied on the funding and institutional support from the developing Soviet industry and also established an academic base at Moscow State University, where Mandelstam helped train a new generation of physicists. Their research programs eventually diverged from those followed by Braun and his pupils in Germany in two fundamental aspects. While the origin of many of his ideas and approaches, and the main thrust of his efforts, remained focused on radio physics, Mandelstam understood that similar powerful methods and the common conceptual apparatus of the mathematical theory of oscillations could also very effectively apply to unresolved problems in other branches of physics, including optics, electronics, acoustics, mechanics, control devices, and the quanta. Many of his students expanded into these various research fields, and more difficult problems that they encountered required the use of nonlinear oscillations, the mathematical method that helped establish the Mandelstam school as a major pioneer in the emerging field of nonlinear physics.[14]

The School of Oscillations made great strides during the 1930s and expanded institutionally. By 1936 it included a network of six important research institutions in three cities: FIAN and Moscow State University in Moscow; the Leningrad Electro-Physical Institute (LEFI), the Industrial Institute and the Central Radio Laboratory in Leningrad; and the Gorky State University in Gorky. Mandelstam shunned administrative positions and responsibilities but consulted and provided intellectual guidance to a wide network of scientists, engineers, and technicians working in academic institutions, applied research labs, and industrial settings, effectively ensuring what they regarded as a "unified research strategy." The Soviet state's view of radio and related technologies as an important priority for the rapidly modernizing country helped support a number of research programs of the Mandelstam school. Reflecting the high prestige and resources granted to the field, radio physics was recognized as a separate academic discipline in the Soviet university system and curriculum. The School of Oscillations' research style did not separate fundamental science from technology, but successfully developed novel approaches in basic science in conjunction with many practical applications and technological inventions, to the liking of Soviet officials.[15]

Circa 1930, nonlinear phenomena and mathematical methods became a major preoccupation for many scientists in the School of Oscillations. The initial impetus came from the analysis of some radio devices but developed into a general understanding that the physical world was essentially nonlinear and required a new, more sophisticated and rigorous mathematical treatment. The major theoretical

[14] Physical systems are usually idealized so that they can be described by linear equations with relatively simple solutions. The next level of complexity, for example even a simple pendulum with oscillations that are not too small, requires nonlinear differential equations.
[15] Pechenkin 2019.

breakthrough in that direction came with the concept of self-oscillation. Alexander A. Andronov (1901–1952), one of Mandelstam's first students who also possessed outstanding mathematical skills, discovered a large class of non-ideal systems—with resistance or friction, and also with a permanent source of energy—for which the resulting behavior takes the form of stable undamped oscillations with characteristic parameters determined by inner features of the system itself, rather than its initial conditions or external force. Andronov labeled such phenomena "self-oscillations," understood them as essentially nonlinear, and proceeded to develop a sophisticated mathematical apparatus capable of describing their frequent occurrences in the real world. As a collective effort, other members of the School of Oscillations enriched that framework further, into what became known as the general theory of nonlinear oscillations, and applied it to solve challenging problems in diverse range of fields, including radio physics, acoustics, mechanics, chemistry (periodic reactions), and biology. In the words of Amy Dahan Dalmedico, "Self-oscillations provided the basis for Andronov's elaboration of the new paradigm of nonlinear physics that Mandelstam had called for."[16]

By the mid-1930s the school had developed the analysis for several paradigmatic examples of self-oscillating systems that were described in textbooks and used for the training of subsequent generations of students. The first such textbook, *Theory of Oscillations*, written by Andronov, Semion Khaikin, and Alexander Vitt, was published in 1937.[17] Among the self-oscillating systems that could produce undamped oscillations were musical instruments, pendulum clocks, and vacuum tubes. The first fundamental question handled in those studies concerned the transformation from a permanent, non-periodic source of energy, for example constant blowing, lowering of weights, or constant tension from a power supply, into a periodic, oscillatory behavior by the system. Further questions focused on various factors that determined and influenced the properties of self-oscillations, their form and frequency, and in particular the characteristics of the stationary oscillations, which occur when the saturation effect takes place, namely when one of the system's parameters reaches a physical limit. In 1950 Gabriel Gorelik, one of Andronov's collaborators in Gorky, published another influential textbook, *Oscillations and Waves,* with additional paradigmatic examples and applications of the theory of oscillations. Radio physics still remained the main area of application of its basic concepts, but further extensions and elaborations of the theory included an ever widening range of disciplines, from nuclear physics to astronomy, from biology to geophysics, and control devices.[18]

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[16] Pechenkin 2002; Dalmedico 2004, on 237. Unlike the more familiar forced oscillations caused by a periodic external force, self-oscillations are sustained by a non-periodic source of energy and do not depend on initial conditions.

[17] Andronov and Khaikin 1937. Alexander Vitt was arrested in 1937, during the Stalinist purges, and his name did not appear on the title of the first printed edition. A condensed English translation was published as part of the project on nonlinear differential equations under contract with the Office of Naval Research, edited under the direction of Solomon Lefschetz. See: Andronov and Khaikin 1949.

[18] Gorelik 1950.

The tradition of the School of Oscillations demonstrates that already before World War II, Soviet physics developed and sustained some of the important features that have more often been seen as characteristic of the postwar style of academic physics, including close entanglement between fundamental theory and the practical development of technological gadgets, interdisciplinarity, and the abandonment, at least in the actual practice, of the restrictive ideology of pure science.[19] We shall now see that those features became important and necessary, although not yet sufficient conditions for the invention of the maser, the account of which requires several additional factors associated with the militarization of physics research after World War II.

2. Militarization and Secrecy

During Prokhorov's first years as a graduate student in FIAN's Laboratory of Oscillations, he took part in a major study on the propagation of radio waves through the ionosphere using a special rangefinder designed by Mandelstam and Papaleksi. Their apparatus used radio-interferometry to measure distances and the velocity of propagation of radio waves in different conditions with high accuracy.[20] With the start of the war in 1941, Prokhorov interrupted his doctoral studies and volunteered for military service. Lieutenant Prokhorov served in the infantry division in which he used his technical skills in reconnaissance. After having been wounded twice and demobilized from the army, he returned to FIAN and resumed his graduate studies in 1944.[21] His new research assignment linked the theory of nonlinear oscillations with one of the major tasks of science during World War II—the development and application of radar technologies. Prior to the war, several of Mandelstam's collaborators worked as consultants for the military and in 1934 demonstrated to Soviet military officials the feasibility of radiolocation. Several poorly coordinated research groups yielded promising results and tested the first prototypes of radar for the Red Army as early as 1939. The start of the war, however, disrupted most of these activities. A well-funded and coordinated radar program was resumed by the Soviet military only in 1943, with allied help.[22]

By the time Prokhorov returned to his scientific work at FIAN in 1944, radiolocation had moved up to the top of research priorities for physicists. The Laboratory of Oscillations defined its main focus as "extremely relevant present questions on generation, modulation, and application of super-high-frequency oscillations," i.e., microwaves used in radiolocation. Its researchers busied themselves with developing nonlinear methods to create a theory suitable for microwave frequencies.[23] Prokhorov's dissertation, accordingly, dealt with the problem of frequency

[19] Forman 1995; Leslie 1993.
[20] These methods helped Soviet mathematical physicists Boris Vvedensky, Vladimir Fock, and Mikhail Leontovich (the latter a student of Mandelstam) develop and improve the theory of propagation of radio waves. See: Wait 1959.
[21] Prokhorov 1996.
[22] Erickson 1972; Kobzarev 2007.
[23] Prospective plan for 1944 on the theory of oscillations and radio-physics by Sergei Vavilov, *Archives of the Russian Academy of Science* (ARAS), 532-1-90, l. 10.

stabilization of tube generators. He obtained his degree of Candidate of Sciences (*kandidat nauk*, roughly the equivalent of a Ph.D.) in 1946.

That work, which Prokhorov conducted under the supervision of Sergei Rytov, can illustrate how the theory of nonlinear oscillation handled real devices and practical problems. Although not directly part of a military radar project, the laboratory worked on general theoretical tasks related to that overall goal. As Rytov later recalled, "The appeal of the work on stabilization of frequency was not accidental, but dictated by the 'social needs' of that time. Radiolocation, radio communication, television: they all demanded generators with more and more stable frequencies."[24] Rytov had improved the small parameter perturbation method to make it applicable to study frequency stabilization and guided Prokhorov's and another graduate student, Mark E. Zhabotinskii's, work on the stability of a tube generator with quartz stabilizer.[25] Their theoretical treatment predicted original phenomena that were later verified experimentally, such as the existence of islands of stability amid mismatching intervals in some specific conditions. In a separate paper addressed to engineers, Zhabotinskii provided an intuitive picture of the stabilization process and a summary with calculated formulas for stable frequencies that could be used to produce more stable generators of microwaves.[26]

The three collaborators, Rytov, Prokhorov, and Zhabotinskii, received the 1947 Prize for best work in radio physics, named after their late teacher, Mandelstam, who had died in 1944.[27] Their research was conducted in the spirit of the School of Oscillations and in accordance with its characteristic approaches. Starting from sophisticated mathematical methods, it proceeded to concrete applications towards solving an important practical problem, with results expressed in engineering language and materialized in workable devices. The same pattern characterized many other research programs developed by Mandelstam, Andronov, and their collaborators and reflected general expectations placed upon Soviet physicists. The general prospective plan for their institute, FIAN, developed by Vavilov in 1944, displayed the typical Soviet tendency to define the value of a scientific project in terms of its possible future applications, rather than its contributions to pure knowledge as such. Paul Forman identified a somewhat similar tendency in postwar American physics, namely the "gadgeteering," that steered physicists' research goals towards the development of devices such as atomic clocks and, eventually, the maser and the laser.[28]

In both countries, postwar improvements and developments in radar technology demanded new methods of generating radio waves with ever shorter wavelengths, from the centimeter into the millimeter region, where the existing technology of generators based on vacuum tubes came to its technical limit. Joan Bromberg described the demand for new reliable sources of microwaves as coming from two sides. The military wanted more compact sources of millimeter-waves for reducing the weight of guided missiles and radars, and for greater se-

[24] As quoted in Prokhorova 2006, on 48–49.
[25] ARAS, 532-1-122, l. 1–10.
[26] Rytov et al. 1945; Zhabotinskii 1946.
[27] Rytov et al. 1948.
[28] See note 23 (Prospective plan for 1944…); Forman 1996.

crecy in short-range communications. A new subdiscipline in physics, microwave spectroscopy and its growing cohort of researchers, utilized decommissioned devices from the wartime radar project and applied them to the study of atomic and molecular spectra in previously unexplored wavelengths circa and below 10 cm. For many important molecules, the absorption spectra lay in the millimeter range and required corresponding sources of radiation.[29]

In 1948 Prokhorov started a new, independent research project that eventually formed the basis of his second, more advanced dissertation for the degree of Doctor of Sciences (*Doktor Nauk*), which he obtained in 1951. This time he moved beyond the core focus on radio physics, but followed the School of Oscillations' interdisciplinary agenda by bringing its methods and approaches to a neighboring laboratory in FIAN that worked on nuclear physics. As part of the Soviet atomic bomb effort, FIAN built an accelerator of particles, the synchrotron, and used it for the study of nuclear reactions. In 1944 Dmitry Ivanenko and Isaak Pomeranchuk predicted what eventually came to be called the "synchrotron radiation," which determined the limits of possible energy acquired by accelerating particles. For nuclear physicists, the effect presented a major difficulty for further improvements in accelerating power of the synchrotron, but Prokhorov wanted to investigate its potential useful application as a possible new source of microwave radiation.[30] This time he started supervising his own students who formed the core of his future research group. Since the fall of 1948 he was helped by Basov, a second-year student of the Moscow Mechanical Institute who joined the laboratory as an engineering assistant. The following year Prokhorov's group acquired their own accelerator, a betatron. With the device came its handler, Alexander I. Barchukov, a student of the Bauman Moscow State Technical University who was already familiar with the accelerator technology.[31]

Working at the intersection of atomic and radio physics, Prokhorov studied experimentally the properties of the synchrotron radiation. While important for the functioning of the accelerator itself, then one of the newest technologies in high-energy physics, the results could also provide a practical device, a new kind of generator of microwaves, or so, at least, was Prokhorov's hope.[32] According to his analysis, the power of non-coherent radiation emitted by electron beams in the synchrotron was proportional to the number of electrons, N, while the power of coherent radiation, due to electrons moving in bunches, could be proportional to N^2 for electron beams with a high degree of bunching. Electrons circulated inside the synchrotron with a frequency equal to that of the high-frequency external field used to accelerate them. The synchrotron radiation included many higher

[29] Bromberg 1991, on 13–14.

[30] FIAN physicists also worked on another possible strategy for generating short microwaves based on the Cherenkov (or Vavilov-Cherenkov) radiation, which they had discovered in the 1930s. See: "Cherenkov, Pavel Alekseevich" 2008. In the United States, Townes also explored the strategy of using the Cherenkov effect for microwave generation. See: Forman 1992.

[31] Prokhorova 2006.

[32] Basov later recalled: "In our investigations, we aimed at the creation of such radiation sources that would continuously cover a wide range of centimeter waves." See: N. G. Basov, interview by Arthur Guenther, 14 September 1984, Niels Bohr Library & Archives, American Institute of Physics (AIP), College Park, MD USA, http://www.aip.org/history-programs/niels-bohr-library/oral-histories/4495 (last accessed 27 November 2019).

harmonics, permitting the generation of much shorter waves. In Prokhorov's investigation, the frequency that corresponded to the 16th and 24th harmonics generated 3 cm and 2 cm wavelength, correspondingly, with the achieved power output of about 10^{-6} W. He estimated that the synchrotron could be used as a generator of microwaves ranging from 1 mm to 0.1 mm with power output between 10^{-6} W and 10^{-4} W, "considerable values [then] hardly achievable by other methods," he concluded.[33]

Though useful for the analysis of accelerators and their radiation, the results ultimately proved somewhat disappointing: the synchrotron radiation was still too weak and incoherent for a practical generator of microwaves. Eventually, the synchrotron would not be able to compete with other, more powerful generators in the centimeter-wave region. Based on his estimates for millimeter waves, Prokhorov still expressed a hope that with a significant increase in the number of accelerating particles, the synchrotron could be used as a source of shortwave radiation for the needs of spectroscopic research.[34] In 1951 the field of microwave spectroscopy was still an American specialty, practically nonexistent in the USSR, where wartime military radar equipment was not yet made accessible to academic researchers. But Prokhorov's synchrotron radiation project was classified, not so much because of its direct interest to the military, but because of its association with the particle accelerator, a device initially built as part of the Soviet atomic bomb project. The results of his research were published only in 1956, when it became sufficiently clear that they would not lead to a new powerful generator of microwave radiation. Safely declassified, they were still original and relevant enough as a study of the synchrotron radiation to warrant publication in an academic journal.[35]

The two American physicists who conceived of the principle of the maser, Townes and Joseph Weber, had also been involved with the development of radar technology during and after the war. The historical connection between the maser and military-related radar research, and with the classified quest for new schemes of generating microwaves, is an established and well-studied phenomenon in the American case, but has not been previously discussed as part of the Soviet path towards the maser.[36] It is possible to conclude now that, similar to their American colleagues, Prokhorov and his first students also took part in the classified search for new technologies to generate microwaves, with a view towards their possible applications in military radiolocation. In their later comments on the development of their research on masers and lasers, the Soviet physicists, just like their American counterparts, did not want to acknowledge this military connection. Such denial relied, in part, on standard secrecy restrictions, and in part on the fact that after 1955, military-related classified research was losing its mantle of prestige in the eyes of many Soviet scientists and the science-interested public, who were increasingly looking at international-oriented, basic research as a more prestigious

33 Transcript of the defense session. ARAS, 532-1-194. l. 15 – 16.
34 ARAS, 532-1-194.
35 Prokhorov 1956.
36 On the crucial importance of the radar project as a source of both expertise and hardware for the subsequent development of quantum electronics, see: Bromberg 1991; Forman 1995.

and respected occupation for academic scientists. In later accounts, Prokhorov and his collaborators preferred to describe their invention of the maser as originating from fundamental scientific concerns with the development of microwave spectroscopy.[37]

While present in both cases, the degree of military involvement was not the same, however. In the US, Townes had been much more explicitly and centrally involved with military projects, as researcher, consultant, and manager of classified work. By comparison, Prokhorov and Basov were full-time employees in an academic research institute, FIAN, which had a share of its funding coming from military projects and a part of its research conducted in secrecy, but still primarily focused on openly published investigations in physics even during the most militarized period, 1947 to 1953. Still, even if their part-time involvement in classified research was only potentially related to possible military applications, such an awareness must have been present in their minds, at least rhetorically. Among Prokhorov's first publications was a short postwar paper in the popular science magazine *Nauka i Zhizn* (Science and Life) and a separately published booklet explaining to lay audiences the fundamentals of military radiolocation. The texts reveal his familiarity with radar physics and an understanding of the importance of his work on frequency stabilization and new schemes for the generation of short microwaves for radar technology.[38]

Prokhorov's classified work on the synchrotron radiation coincided with the last years of Stalin's rule, the period of utmost secrecy, Cold War paranoia, and spy mania in the Soviet Union. While many Soviet scientists privately and grudgingly disapproved of the excessive secrecy, many others, especially in the Prokhorov generation, who rose to professional maturity between 1940 and the mid-1950s, considered classified work on military tasks highly important, prestigious, and rewarding. The values of the Soviet *frontovik* (war veteran) generation were formed under the decisive influence of the Great Patriotic War and continued to generate that ethos also through the early Cold War years. A secretary of the Komsomol organization at the Leningrad Electro-Technical Institute captured the mood of many of Prokhorov's contemporaries when he affirmed in an interview that people of his time were "deeply influenced by the spirit of the frontovik generation," characterized by war-related virtues such as heroic patriotism, loyalty, collectivism, and self-sacrifice, which dominated the landscape of the Institute until the mid-1950s.[39] Both Prokhorov and Basov became members of the Communist Party in the early 1950s and later performed leading roles in defense-relat-

[37] For example, N. G. Basov in his oral history interview (see note 32) denied any link with military investigations. Such denials were more typical of the 1980s rather than the 1950s. In 1984 Soviet physicists were publicly opposing Reagan's Strategic Defense Initiative. In an interview recorded on the same day as Basov's, Prokhorov voiced his opposition to military applications of lasers: "I wish that the dream of ah… the war by lasers, I think so, it's rather silly thing, and that one way in which we must not go." Prokhorov, Aleksandr, interview by Arthur Guenther, 14 September 1984, Niels Bohr Library & Archives, AIP, College Park, MD USA, http://www.aip.org/history-programs/niels-bohr-library/oral-histories/5048 (last accessed 27 November 2019).

[38] Prokhorov 1946; Prokhorov 1948.

[39] Fürst 2006, on 224–225.

ed research in the Soviet Union. Both remained supporters of the socialist system to the end of the Soviet Union.[40]

Many physicists of that generation accepted as normal and justified the mobilization of science and scientists for defense-related projects, worked in mission-oriented institutions, often in relative isolation, under conditions of utmost secrecy and surveillance, without permission to publish openly their most important results and receive public credit for them. This especially applied to scientists who were involved in the atomic bomb research, such as Igor Kurchatov, who saw his scientific responsibility for that project as a direct continuation of the wartime effort, requiring comparable discipline and self-sacrifice.[41] Thus, secrecy and compartmentalization, the essential elements of the history of the maser in the United States, were also strongly present on the other side of the Iron Curtain. Growing from the entanglement between physics and military research during and immediately after World War II, this similarity extended over matters of organization, professional ethos, and management of major projects in science. It also affected, as we shall see in the next section, matters of intellectual content, ideas, and inventions.

3. Catching up and Surpassing: from Microwave Spectroscopy to the Maser

After Prokhorov defended his dissertation and moved up the academic ladder from a graduate student to a senior research associate at FIAN, his living conditions began to improve dramatically. Not only did his salary rise significantly, but he also acquired other, no less important privileges of Soviet society, such as access to stores with better quality food and goods, and a small plot of land for a *dacha* outside Moscow. For a while, however, he still had to live in a crowded 15.5 m^2 room which he shared with his wife, son, and mother-in-law, and with one table used for both work and eating. In summers he could have a little more privacy with an improvised writing desk made of a piece of plywood nailed to a corner of his balcony. His living conditions improved in 1950 when the family moved to a new apartment of three rooms in a condominium built specially for FIAN's workers, located near the new building of his institute.[42] Prokhorov's new living standard reflected not only his academic degree and position, but the general privileged status of science in the postwar Soviet Union. Those privileges came with strings attached. In exchange for their improved funding and prestige, Stalin expected Soviet scientists "not only to overtake but also … to surpass the achievements of science outside the boundaries of [their] country."[43] Although his pri-

[40] In the 1980s, Prokhorov and Basov advised the Soviet government on military science and security. "Their opinion was considered to be very important. The leaders agreed to what they said, even if they didn't understand what they said." See: Hey 2006, on 41. For the American side of the story, see: Wilson 2015. Prokhorov also signed an official letter attacking the dissident Andrei Sakharov for the views on nuclear deterrent published in *Foreign Affairs.* See: Dorodnitsyn et al. 1983.

[41] Kojevnikov 1999, on 241.

[42] Prokhorova 2006.

[43] "Speech Delivered by Stalin at a Meeting of Voters of the Stalin Electoral District, Moscow," 9 February 1946, History and Public Policy Program Digital Archive (Gospolitizdat, Moscow, 1946), https://digitalarchive.wilsoncenter.org/document/116179 (last accessed 27 November 2019).

mary audience were scientists working on the Soviet atomic project, Stalin's message, and the associated privileges, did not remain restricted to nuclear physics, but extended to other scholarly fields as well. Soviet physicists, in particular, were expected to compete with Americans across the entire spectrum of advanced academic fields, old and new.[44]

One such novel field, microwave spectroscopy, emerged in some American laboratories just before the end of the war, but boomed especially during the early postwar years, when many physicists returned to their universities armed with expertise and hardware byproducts of the wartime radar project. According to Paul Forman, microwave spectroscopy became the "premier example of a flourishing field of physical research created—in every sense—by radar."[45] The results of its investigations also influenced significantly other prestigious directions of research in atomic and nuclear physics. The new, much more accurate measurements of the absorption spectra of atoms and molecules enabled important conceptual advances in quantum electrodynamics and forced theoreticians to reformulate theoretical models of nuclear physics to fit the new experimental data.[46]

With the defense of his *Doktor Nauk* dissertation in 1951 (the second academic title in the Soviet system, comparable to the German *Habilitation*), Prokhorov became an accomplished researcher ready to lead his own field of investigations and a laboratory in the institute. Following a suggestion by Sergei Vavilov, he chose microwave spectroscopy as a branch of science that was not yet developed in the USSR, but was rapidly advancing in the US.[47] Most spectroscopic research was unclassified and openly published in academic journals, but in compliance with common patterns of the time, it was still useful, for the purpose of connections as well as funding, to have at least part of the research activities associated with some secret military-related project. According to archival reports that summarized the work of Prokhorov's laboratory starting in 1952, about a third of its research was classified and aimed at precise "determination of nuclear moments, as ordered by the decision of the USSR Council of Ministers."[48] This aspect of his work was obviously, even if marginally, related to the atomic bomb project. In particular, precise measurements of nuclear moments were supposed to help theoreticians improve the nuclear shell model, which struggled to have its numerical calculations conform to available experimental data.[49] Prokhorov's move to a new direction of research thus appears to have been motivated by the general stimulus to catch up with Western physics in a novel field that was also relevant for prestigious and militarily important nuclear physics.

His group's first challenge was to build a spectroscope with high sensitivity and resolution, similar to those "described in general terms in the foreign literature."[50] In the meantime, they mastered the new field theoretically and suggested solutions

[44] Kojevnikov 2004; Kojevnikov 2011.
[45] Forman 1995, on 422.
[46] Schweber 2014.
[47] Interview of Aleksandr Prokhorov (see note 37).
[48] Laboratory report of 1955, ARAS, 532-1-251. l. 83-39.
[49] Recently published archival report: Basov 1997a; and Basov's 1953 dissertation published in the same volume, 51 – 123.
[50] Basov 1997b, on 17.

and possible improvements that, in their own estimate, matched the level of foreign research in theoretical quality, while lagging behind in hardware. Their microwave equipment, as in the American case, came from radar devices that were still manufactured by the Soviet industry but no longer needed by the military. Initially, they acquired a reflex klystron that produced radiation of wavelengths between 5 cm and 2.6 cm. By using its second harmonic, they could generate waves twice as short, but at reduced power and sensitivity of the spectroscope, which still did not allow them to study molecular absorption spectra below 1.3 cm.[51] By comparison, transmitters of the k-band radars widely available to US physicists after the war could generate radiation of wavelength 1.25 cm with enough power to be employed in radars, much more than what a spectroscope required.[52]

Prokhorov's next problem, common for all spectroscopists, concerned the limits on spectral resolution. In a gas of molecules, some are randomly moving towards the incoming radiation, while others away from it, which affects the frequency of the absorbed radiation due to the Doppler effect. The resulting Doppler broadening of the spectral lines registered by the detector can prevent the identification of two separate lines, if their frequencies are close. A possible solution was already discussed in the literature, following the proposal by the Princeton University physicists George Newell and Robert Dicke to replace a gas of randomly moving molecules with a beam, in which all molecules move in the same direction. By 1952, several teams of American researchers were already constructing or operating microwave spectroscopes with molecular-beam absorption.[53]

The technology of molecular beams had been in use in physics since the late 1930s, though for somewhat different purposes. One of the leading teams, Isidor Isaac Rabi's group at Columbia University, employed them in a method to determine magnetic moments of atomic nuclei, under the name of "molecular beam magnetic resonance spectroscopy."[54] In the mid-1940s, Rabi's collaborator Harold Hughes proposed a further extension of the method to study molecules with large dipole moments. Electric resonance spectroscopy was analogous to the magnetic resonance method, but used a non-uniform electric field, instead of a magnetic field, to manipulate the molecular beam.[55] In the resonance method, the absorption was measured by the change in intensity of the molecular beam rather than by the change in intensity of the radiation, as was more traditional for spectroscopy.

Upon reviewing the literature, Basov and Prokhorov opted to construct their own version of a microwave spectroscope that combined different existing ideas in a new pattern. They planned to replace the gas with a molecular beam in order to decrease the Doppler broadening, to rely on Hughes' electric method to create and manipulate the molecular beam, but to measure the absorption by the outbound radiation, rather than by the intensity of the beam, as in the resonance method. According to their calculations, they expected such a combination of the molecular

[51] Laboratory report of 1955 (see note 48); Basov 1997b; Kojevnikov and Mokrova 2003, on 117.
[52] Bromberg 1991, on 13.
[53] Newell and Dicke 1951; Forman 1992.
[54] For the history of the molecular beam method and Rabi's group, see: Goldstein 1992; Forman 1995, on 404–407.
[55] Hughes 1947.

beam resonance method with microwave spectroscopy to decrease the broadening of spectral lines from 60 kHz, typical for gases, to approximately 8 kHz.[56]

They first presented their proposal for building a molecular-beam spectroscope on 22–23 January 1953, at a classified conference on magnetic moments of nuclei. According to the proceedings, their calculations included an additional original idea: using the non-uniform electromagnetic field to separate the molecules in the beam by their quantum energies. A typical molecular beam leaves the oven as a mixture of molecules, some in the ground state and some in excited, higher-energy states. The difference between the numbers of molecules in these states, which is usually a fraction of a percent, determines the rate of quantum absorption. If one can separate and only put into the cavity those molecules that are in the ground state, the spectroscope's sensitivity can increase by up to a thousand times. Basov and Prokhorov possibly arrived at this idea as a trick to compensate for the low power of their microwave radiation source.[57]

The idea of separation opened up yet another, previously undiscussed opportunity. Once the molecules were separated, explained Basov and Prokhorov, a new spectroscopic method was at hand, namely to study emission spectra instead of absorption spectra. For this, one had to send through the cavity those molecules that were in an excited, higher energy state. Their flight time through the cavity was typically much shorter than the time needed for spontaneous emission, but the incoming radiation could still cause induced emission. "The observed radiation will be, of course, induced," wrote the authors, concluding that "if the cavity has a good enough quality factor … the probability of emission of molecular energy approaches one. All the molecules passing through the cavity irradiate."[58]

In their January 1953 presentation, Basov and Prokhorov did not yet mention the capacity of such a device to generate or amplify radiation; they talked about it only as a spectroscope. The possibility that "Using a molecular beam in which the molecules in the lower state of the transition under study are absent, we can make a molecular generator," was first discussed by them by the end of the year in an extended, improved version of their conference presentation, the paper submitted for publication in January 1954. The last pages of that paper discussed the working principles and estimated parameters of such a device:

> The sorted out molecular beam, in which molecules in the lower state of the transition under study are absent, is passing through a cavity. During the flight inside the cavity, part of the molecules undergoes transitions from the upper to the lower state, imparting their energy to the cavity. If intracavity losses are smaller than the emission power of molecules, *self-excitation* takes place and the radiation power in the cavity increases up to the value determined by the *saturation effect.*[59]

[56] Paper presented at the meeting on the magnetic moments of nuclei, January 22-23, 1953, ARAS 1522-1-59. l. 36-47. The paper was later reprinted as Basov and Prokhorov 1997a.

[57] They estimated that molecule separation could increase the spectroscope sensitivity a thousand times: Basov and Prokhorov 1997a, on 40–41. According to Basov 1997a, the low power of their microwave source limited the sensitivity of the spectroscope.

[58] Basov and Prokhorov 1997a, on 41.

[59] Basov and Prokhorov 1954, on 437, emphasis added. The submission date is 19 January 1954. However, according to some accounts, the paper was initially submitted in December of 1953, but the need for a small numerical correction caused its resubmission one month later. The paper was published in October of 1954. See: Karlov et al. 2010, on 34.

Basov and Prokhorov's understanding of the maser principle referred to the condition of self-excitation and the energy of the stationary state of the oscillator determined by the saturation effect. It was based upon the concept of self-oscillation as developed by the Soviet school of oscillations and provided yet another example of a self-oscillating system.[60] Their path towards the invention of the maser, as revealed by the documents, can be summarized in the following steps. They put together, first, the proposal by Newell and Dicke to eliminate the Doppler broadening by replacing a gas with a molecular beam; second, the method of manipulating molecular beams by non-homogeneous electric fields developed by Hughes; and third, the conceptual apparatus of the Soviet theory of oscillations which permitted them to envisage that under specific conditions, stimulated radiation would build up inside the cavity and allow the device to amplify and to generate radiation. We are now in a better position to compare the differences and the similarities between the Soviet and the American conceptualizations of the maser.

4. Comparative Approach: Experiment and Theory in the Invention of the Maser

In the course of 1953, the Soviet and the American work towards the maser were on converging paths. Townes conceived his initial idea of a microwave generator based on stimulated emission in the spring of 1951, and in 1952, under his supervision, his Ph.D. student James Gordon and postdoctoral fellow Herbert Zeiger started putting together experimental pieces of the possible device. In 1953 they adjusted the project as aiming at a microwave spectroscope and amplifier, just to be sure that even if the generator did not work, Gordon would still have an accomplishment to defend his dissertation.[61] Basov and Prokhorov moved in the opposite order: in 1952, they started working towards a microwave spectrometer, before eventually shifting towards an amplifier and a generator. At the time, neither side was aware of the other's project.

Archival records indicate that Basov and Prokhorov learned about Townes's project in the second half of 1954, after the *Physical Review* issue with a short paper by Gordon, Zeiger, and Townes reached the USSR. In that letter to the editor, the authors described in general terms the working principle of the "molecular microwave oscillator" and announced its successful operation as a high-resolution microwave spectroscope.[62] The Soviets then hurried up to publish their own detailed "Theory of the Molecular Generator and Molecular Power Amplifier" in the *Proceedings of the USSR Academy of Sciences.*[63] That they took almost

[60] The saturation effect occurs when a parameter of the system, here the radiation power, reaches its physical limit. This is a nonlinear effect. See: Gorelik 1950.

[61] Forman 1992; laboratory report of 1955 (see note 48).

[62] Gordon et al. 1954. Earlier progress reports appeared in the *Quarterly Report of the Columbia Radiation Laboratory*, an internal publication that was available in Columbia University's Library. There is no indication that the Soviet team was aware of these reports and of Townes' project prior to the publication in the *Physical Review.* Starting with the second half of 1954, the documents by Basov and Prokhorov systematically included references to Townes' work.

[63] Basov and Prokhorov 1955a.

two years to submit that paper, which conceptually was not far beyond the paper delivered in January 1953, indicates that they had not been aware of the work of Townes's team. With an English version of the paper in hand, in early April 1955 Prokhorov flew to England, where he met Townes for the first time and discussed their approaches to the new device face-to-face.[64] By comparing the early papers and lecture notes by the Soviet and the American teams, we can analyze how their respective scientific cultures influenced their different understandings of the maser.

In the first official presentation specifically devoted to the molecular generator, at the meeting of the All-Union Society of Radiotechnology and Radiocommunication in October 1954, Basov and Prokhorov defined the device as a "self-oscillating system that uses the energy associated with transitions between different molecular levels."[65] Their early explanations and calculations of the new device's operation were usually based on an analogy with the vacuum-tube generator, the paradigmatic, well-studied example for the theory of self-oscillations. The cavity and the electromagnetic radiation inside it played roles similar to the circuit and the electric charge for the vacuum tube. Many of the terms and concepts used in the analysis were familiar to radio engineers. Prokhorov would later explain the analogy in his Nobel lecture:

> As is well-known from radio engineering, any system able to amplify can be made to oscillate. For this purpose, a feedback coupling is necessary. A theory for ordinary tube oscillators is well developed in the radio range … Therefore the condition of self-excitation for the quantum oscillator [maser or laser] should be written in a similar way as for a tube oscillator.[66]

As with other self-oscillating devices, their theory of the maser was based from the outset on a nonlinear differential equation. That definition dictated the system's characteristics to be observed (namely, the condition of self-excitation of the stationary state), the main questions to ask (What quality factor Q was necessary for self-excitation to happen? What are the features of the stationary state?), and how to answer them. The maser differed from the previously studied self-oscillating systems by its specific source of energy, which was quantum rather than classical. That part of the system, the beam containing a large ensemble of quantum oscillators (molecules), had to be described with the help of quantum statistics. The resulting semiclassical theory combined a quantum approach for molecular transitions and a classical, but nonlinear theory for the description of the cavity radiation.

Overall, the Soviet path towards the maser can be characterized as theory-driven. Their command of a relatively advanced theory allowed Basov and Prokhorov to calculate, envision and predict certain characteristics of the system, while the actual building of the device lagged behind due to the lack of sufficiently advanced hardware. As an example, in one of the first papers they calculated

[64] Basov and Prokhorov 1955b.
[65] Basov and Prokhorov 1997b, on 127.
[66] Prokhorov, Alexander, "Nobel Lecture: Quantum Electronics, 1964," 110–16, on 112–113: http://www.nobelprize.org/nobel_prizes/physics/laureates/1964/prokhorov-lecture.html (last accessed 27 November 2019). "Mandelstam's typical way of speaking," a comment on this passage in Pechenkin 2002, on 291.

the minimum quality factor Q and the maximum power for a molecular generator based on quantum transitions in cesium fluoride CsF, which would generate 3.7 cm waves. Having concluded that the state-of-the-art technology could not produce a cavity with Q sufficient to achieve the self-oscillation regime, they argued that it would be necessary to use molecular beams with higher than usual density. For the usual molecular beams, they predicted, the device could still be useful as an amplifier and spectroscope of very high resolution and very low noise, but not as a quantum generator.[67] Guided by similar calculations, from 1954 on, Basov led the work on technical improvements of their apparatus, focusing especially on the quality of the cavity and the focuser that sorted the molecules, in order to increase the density of the molecular beam and eventually achieve the generation regime.[68]

According to the initial announcement by Gordon, Zeiger, and Townes, "[a]n experimental device, which can be used as a very high-resolution microwave spectrometer, microwave amplifier, or a very stable oscillator, has been built and operated." This formulation conveys the absence of the general concept of self-oscillating systems. They refer to the maser simply as an "experimental device" defined by its functions—what it could do—rather than its general type. Correspondingly, Gordon described the maser in mostly operationalist terms, presenting the block diagram of the apparatus, its main parts and the working principle, and the conditions in which it could function as an oscillator, an amplifier, or spectrometer. He discussed the power, stability of oscillation, noise figure, and resolution (spectral linewidth) as experimentally measurable, rather than calculated, characteristics. His only calculation concerned the spectral linewidth, which they estimated at 4 kHz, of the same order of magnitude as the observed value of 6–8 kHz. From the use of the device as spectrometer, they also reported experimental measurement of the hyperfine structure of ammonia inversion transitions.[69]

Citing the American announcement of the maser in their October 1954 presentation, Basov and Prokhorov mentioned critically that "no theoretical consideration is given, and the estimate of the linewidth shows that the authors do not understand well enough the working principle of the molecular generator."[70] According to Basov's analysis, the spectral linewidth can either be determined by the time of flight of the molecules through the cavity or by the lifetime of their excited state. In the stationary regime, when the radiation field inside the cavity is intense, the lifetime of the molecules is shorter than the time of flight, in which case the saturation effect determines the spectral linewidth. Gordon's calculated value of the linewidth at 4 kHz depended on the time of flight. Taking into account the saturation effect, or nonlinearity, Basov obtained an estimate of 7 kHz, in complete agreement with the observed values. Later, in response to the Soviet theory of the maser, Gordon, Zeiger, and Townes published their own detailed calculation based on the linear, first-order perturbation theory. They acknowl-

[67] Basov and Prokhorov 1954.
[68] Laboratory report of 1955 (see note 48).
[69] Gordon et al. 1954.
[70] Basov and Prokhorov 1997b, on 127.

edged that when "the molecular transitions begin to saturate," their equation was no longer sufficient for estimating the linewidth and promised that "the effects of this saturation will be considered in detail in a later paper."[71]

The above exchange reveals that thanks to their command of the theory of self-oscillations, the Soviet team relied on a more advanced theoretical understanding of the maser's generation regime as an essentially nonlinear effect that required nonlinear equations for its description. The American path towards the maser can be characterized, by contrast, as gadget- or experiment-driven, relying upon the availability of hardware with advanced characteristics inherited from the wartime radar project. Existing accounts describe the invention of the maser by the Columbia University team as a long process with many experimental iterations, adjustments, and a good deal of tweaking. Between the "early-morning epiphany" on a park bench in Washington, D.C., in the spring of 1951, when Townes wrote his first notes on what would eventually become the maser, and the moment in April 1954, when Gordon broke into a seminar room announcing that he had finally obtained the long-sought oscillations, the anticipated device changed multiple times, from a generator of 5 mm waves to a spectrometer and amplifier of 1.25 cm waves. This evolution was long, costly, and tiresome, which prompted Townes' superiors at the Columbia Radiation Laboratory to recommend the termination of the project, because the chances of success seemed scanty. Townes persisted nevertheless, and the eventual result vindicated his resolve. The novel device quickly attracted much attention, and young physicists showed their interest to move to Columbia University to learn the "maser art."[72] The expression also shows that the work was primarily an experimental improvization with a life of its own, as Ian Hacking would have said.

To be more precise, we can distinguish two levels of theory at work in this case. The first is the Einstein theory of spontaneous and stimulated emission of radiation, the basis of the quantum theoretical analysis of spectral transitions.[73] This level of theory was shared by both teams, who had a similar understanding that the device relied on a new source of energy, the energy of stimulated quantum transitions in the molecular beam. The second level concerns the explanation of the behavior of the radiation emitted by the molecules and interacting with the cavity and the incoming beam. At this level, the practice of the two teams was quite different. Philosopher Ian Hacking has argued that the existence of a mature theory is an important factor in influencing the changing dynamics between theory and experimentation over time. When working in a context in which a well-developed theory is available, scientists usually follow a more deductive approach, whereas the lack of such theory prompts scientists towards inductive approaches and reliance upon experimentation as a more autonomous endeavor.[74] Hacking's distinction seems to grasp well the apparent difference between the Soviet and the American roads towards the invention of the maser.

[71] Gordon et al. 1955, on 1268–1269.
[72] Polykarp Kusch and Rabi put pressure on Townes to abandon the "molecular generator." See: Forman 1992, on 133. The term "maser art" is used by Bromberg 1991, on 24.
[73] Einstein 1917.
[74] Hacking 1983, on 155–165.

5. Conclusions

The investigation of the parallel discovery/invention of the maser principle in the USSR and the USA in the 1950s reveals important comparable trends not only in the development of scientific ideas and research projects, but also in much more general processes underlying the profound transformation of science during the early Cold War era. Basic questions and problems identified and raised by historians who have earlier studied the American side of the story—such as the penetrating effects of military patronage, gadgeteering and compartmentalization, a transition to big science institutions and mass training of scientists, a shift from the ideology of pure science to goal-oriented research, tensions between the national security state and scientific internationalism, changes in the ethos and social standing of scientists, the entanglement between open and classified research, and the scientists' denials of the latter[75]—all these major trends had their deeply meaningful parallels on the Soviet side. An analysis of these processes from a comparative perspective supports the conclusion about a fundamental convergence between American and Soviet science during the postwar period.

This mutual approximation cannot be understood without taking into account the broad social context of the time, namely World War II and the Cold War, and the dramatically increased role of science in politics and society, both in the East and in the West, despite political and ideological differences. Some of the powerful sources of such converging tendencies can be characterized as structural: they reflected similar lessons derived from the wartime experience, the common attachment to progressive modernism, and the rising importance of science for the military. Other sources were relational and depended on mutual learning and frequent borrowing, which could sometimes be acknowledged openly, and sometimes hidden or camouflaged. It is not an uncommon phenomenon that rivals pay increased attention to the chief enemy and often end up, intentionally or as reflex, imitating each other in certain methods and behavioral aspects. The Cold War competition in science and technology exemplifies this tendency.

In the maser case discussed here, the most important structural similarity arguably came from the intimate relationship between science and the military forged by World War II. The fact that masers and lasers were not invented earlier has puzzled some scientists, because many of the necessary concepts and experimental methods had already been at hand before the war, including the theory of stimulated emission and the technology of molecular beams. The practice of combining advanced theories of quantum mechanics with engineering skills and tasks also had its roots in the interwar period, and some scientists, in particular Vladimir Fabrikant in the USSR, did discuss the possibility of using stimulated emission for the generation of radiation, but did not succeed in the practical realization of this idea at the time.[76] The maser only became possible after the war, with the experience physicists acquired while working in large-scale military projects, with increased military funding for research, and with the knowledge and technology created in the process of radar development.

[75] Oreskes 2014.
[76] Lukishova 2010.

The relational convergence during the Cold War offered strong motivations for scientists to follow attentively the work of their rivals, but also unprecedently strong obstacles created by secrecy and by barriers to personal communications. Typically, as in the maser case, scientists had access to openly published works by the other side, which represented only the unclassified portion of the overall research program, while trying to make informed guesses about the rest of the research agenda and the work that remained classified and hidden from public view. This artificial situation, as if deliberately created by the Iron Curtain at the height of the Cold War, helps demonstrate the theoretical point that parallel inventions and technology transfer could take place without much personal contact and tacit knowledge, through the attentive use of formal publications and communications, however censored and restricted.

The convergence of practices still left plenty of room for important differences in style as well as in substance. In the maser story, one of our main tasks as historians was to uncover these differences, which are sometimes obscured by the official story of the case as a parallel discovery and by the joint award of the Nobel prize. Our account has revealed alternative heuristic paths, background in different scientific cultures, a different dynamics between theory and experiment, and significant disagreements in conceptualization and interpretation of the maser by the two teams. Following the personal meeting between Townes and Prokhorov in 1955, their subsequent exchanges, and in the course of extensive further work by many scientists on the development of masers and lasers, such disagreements were usually resolved, or superseded, and their traces made largely invisible. They can nevertheless be recovered and understood with the help of archival sources.

In many other specific cases, however, official stories of the Cold War rivalry tended to adopt an approach that emphasized oppositions, polarities, and made convergence paths invisible or hidden under deliberately different labels. Historians influenced by ideological discourse framed their narrative in such a way as to downplay or brush aside comparable trends and similarities. The converging practices identified in this study had broader implications far beyond the maser story and certainly affected many other research projects and developments in Cold War science that are still awaiting appropriate historical analysis. It is also important to note that the process of Cold War convergence was not limited to science and technology, but extended to other areas of social life, with serious consequences for global developments in that era. Bringing these processes to the focus of historical attention can also bring about a reconceptualization of the accepted narrative of the Cold War.

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