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REVIEW

The Discovery of Magnetic Resonance in the Context of 20th Century Science: Biographies and Bibliography. I: Discoverers of Magnetic Resonance in Matter

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Abstract—This article is a translation of the first chapter from the book "The Discovery of Magnetic Resonance in the Context of 20th Century Science: Biographies and Bibliography". The book, dedicated to the 75th anniversary of magnetic resonance discovery, chronicles the history and bibliography of this major breakthrough in the 20th century physics (in Russian). In it, biographical accounts of E. K. Zavoisky, E. M. Purcell, and F. Bloch, outstanding physicists and fathers of magnetic resonance methods, are given. For each, a path to this discovery and works beyond it are described. Research preceding the discovery of the electron spin resonance and nuclear magnetic resonance as well as the first works in this new field of science are discussed.

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EVGENY K. ZAVOISKY (1907-1976) – DISCOVERER OF EPR

Evgeny Konstantinovich Zavoisky, author of one of the most dramatic discoveries of the 20th century physics, paradoxically, is little known in his country. His recognition is far exceeded by that of Kapitsa, Landau, Semenov, Kurchatov, Artsimovich, Kikoin, Skobeltsyn, or other Soviet physicists working roughly at the same time; his unorthodox thinking, ever-pushing the boundaries of accepted perception, most likely, being the reason. He never belonged to any of the prominent scientific schools. After he had become the member of the Academy of Sciences of the Soviet Union, he continued to perform his experiments with his own hands. Zavoisky saw himself first and foremost as a scientist, not as a "science manager" (the latter was typical for the members of the Academy). His aspirations were directed to the advancement of Soviet science rather than to the advancement of his personal scientific career. "Servant of the state" by his position at the Academy, he nevertheless refused to sign the open letter denouncing dissident Andrey Sakharov, unlike many of his fellow academicians. By no means was electron paramagnetic resonance his only contribution to science, although a stellar one, worthy of a Nobel Prize. He was the father of a whole new field of applied physics – picosecond electron-optical chronography – and thus made it possible for the researchers in plasma physics, nuclear physics, laser physics, astronomy,

Deceased.

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Fig. 1. E. K. Zavoisky. Source: N. E. Zavoiskaya's personal archive.

and biology to investigate ultrafast processes. He was the man behind the advent of polarized nuclei sources for accelerators. As well he was the man behind one of the greatest discoveries in plasma physics – that of turbulent heating. His biography eloquently shows all of his breakthrough accomplishments coming along in spite of the trying circumstances of his life and work (see Fig. 1).

Evgeny Zavoisky was born in Mohyliv-on-Dniester, Ukraine, the Russian Empire, to a family of an army doctor, Konstantin Ivanovich, and his wife Yelizaveta Nikolaevna Zavoiskys [1][1]. The family name has toponymic origins and means, literally, the person who lives behind the river Voya (a tributary of the river Vyatka in European Russia, to the west of the Urals). The name came from a direct ancestor of the family, a clergyman, who settled down at the river Voya early in the 19th century – it was customary at the time in rural Russia to call new settlers by the name of the place they settled down nearby, rather than by their original family names. Grandfather of Zavoisky was the first in the family to leave clergy for the secular employment, his new position demanded a good deal of traveling. His son, Konstantin, farther to Evgeny Konstantinovich, was born in Malmyzh, Vyatka Gubernia (Province). Konstantin Zavoisky graduated from the Military Medical Academy in Saint Petersburg and served as an army doctor in the Far East, Russia, for several years before and during the Russo-Japanese War. In 1908, the family moved to Kazan, where Konstantin Zavoisky obtained an appointment as a doctor at the powder mill.

There were five children in the family, two daughters and three sons, of which Evgeny Konstantinovich was the third child. When the First World War broke out, his father was posted to a field hospital. Then the Russian Revolution of 1917 broke out, and life took a sharp turn for the worse. Konstantin Zavoisky died of a severe illness. In 1921, the family had to relocate back to Vyatka Gubernia to live with the sister of their late farther – she had a kitchen garden, a circumstance that provided the family with a better chance to survive. There, young Zenya[2] was sent to elementary school and first discovered his interest in amateur radio. The provincial capital, Kazan was far better suited for the children to finish their education, so five years later, in 1925, the family returned back to the capital city.

A gifted young man, Evgeny finished secondary school in 1926, and passed brilliantly entrance examinations for the Kazan State University to study mathematics and physics with his family difficult financial situation never stopping him from pursuing his passion for knowledge. He had to take odd jobs, had a lot of household chores to perform, had only his father hand-me-downs to wear, and yet, every day he was walking a long way to get to the University. Undoubted talent of the freshman student was recognized immediately by his professors, among which there were renowned scientists teaching at the University at the time. Evgeny started experimental work at the laboratory early on in his University years, and was, by all accounts, an inquisitive student reading far above and beyond his curriculum.

One of the key influences on his scientific explorations was Professor Vsevolod Alexandrovich Ulyanin (1863-1931) (Fig. 2), an outstanding experimental physicist. The little that is known about the life and work of Vsevolod Ulyanin was researched and published by Zavoisky's daughter, Natalya Zavoiskaya [2]. Ulyanin was brilliantly educated. He studied mathematics and physics at the Imperial University of Dorpat, the Russian Empire (present day University of Tartu, Estonia), the University of Munich, and the University of Strasbourg, both German Empire at the time. From the latter he earned his Doctor of Natural Philosophy degree. Among his teachers were

[1] Ancestral data included below comes from the research by Natalya Evgenyevna Zavoiskaya, who kindly granted us her permission to use the material [1].

[2] The diminutive of Evgeny.

Fig. 2. V. A. Ulyanin, 1928. Source: N. E. Zavoiskaya's personal archive.

Wilhelm von Bezold, Eduard Hagenbach-Bischoff, Wilhelm von Beetz, and W. Voigt, outstanding physicists of the time. August Kundt (1839-1894), a renowned German physicist and a student of Heinrich Gustav Magnus, presumably, had the most important influence on Ulyanin who worked with him on two occasions, late in 1880s and in 1890s. In this curious way, the paths of Evgeny Zavoisky and the USSR most celebrated physicists symbolically crossed there, in Munich: Abram Ioffe, farther of the Soviet physics, studied under the tutelage of and acted as an assistant to Wilhelm Röntgen, most prominent student of Kundt. Vsevolod Ulyanin made a notable contribution to experimental physics, namely to researching photo-effect and to investigating potential for the radio valves to be used in electronic equipment. In 1928, Kazan hosted the Sixth Conference of the USSR Physicists, invitations were extended to foreign scientists as well. It was Professor Ulyanin, a pillar of local academia, who welcomed Soviet and foreign physicists to the Conference.

In 1929, Zavoisky published his first paper, *On Gas-Electric Analogies*, in *The Bulletin of the Kazan State University Student's Circle for Mathematics and Physics*. His undergraduate education was approaching a finishing line, Zavoisky, a student of outstanding talent, was recommended to be enrolled in the postgraduate research program, despite of him inappropriately being of neither working class nor peasant origin – a prerequisite for any kind of career to take place in the post-Revolution Russia. Professor Ulyanin insisted on him being admitted and took him as his postgraduate student. For his thesis, the young physicist chose to investigate potential of radio waves for studying matter.

Unwavering commitment to his chosen field of research was one of the cornerstones of his future accomplishments. After Ulyanin passed away in 1931, Zavoisky went to Leningrad to work at the Central Radio Laboratory, heart of the Soviet radio physics. There, for 8 months, he studied ultra-short waves, their generation and reception. Management of the Laboratory suggested that for his postgraduate thesis he should study super-regenerative receiver. Zavoisky's choice was to pursue two lines of research instead. He committed himself to both the applied research and to the development of a vacuum tube oscillator with an oscillation amplitude and, hence, grid current and anode current, all to the maximum extent depending on stability of the oscillating circuit.

In this he succeeded. In the years of 1932-1933 Zavoisky both designed and experimented with a scheme for an ultra-shortwave super-regenerator, and developed an apparatus highly sensitive to the properties of dielectrics used in the oscillating circuit capacitor. Evgeny Konstantinovich was among the first to study radio wave absorption in the substance by means of this method, widely known today, but novel in the early 1930s. Back then, he was awarded two inventor's certificates. Using frequencies in the short- to ultra-short-wave range, though, could yield no breakthrough results in his studies of either dielectric or electrolyte properties. Meanwhile, the laboratory notebooks of those years, located miraculously in the archives by I. I. Silkin, make it clear that, when experimenting with oscillation frequency, Zavoisky was searching specifically for resonances, i.e., areas of stronger absorption of electromagnetic energy.

In 1933, Zavoisky defended his postgraduate thesis and was appointed Associate Professor (Docent) at the Kazan State University. By mid-1930s, atmosphere at the University had grown increasingly anxious. With the University administration in a state of instability, it was a difficult time for scientific research. In his memoirs, Zavoisky vividly described those years at the University (citation by [3]):

"My memories of that administrative chaos are in bits and pieces. Countless names got jumbled up in my head: Mislavsky, Galanza, Segal … <…>. Rectors did not stick around. N-B. Z. Vexlin was the only one who made a long-term rector. Exuberant, good hearted, but burning up with ideas to revolutionize whatever met his eye, he was convinced that the revolutionary spirit was not to be restrained and, astonishingly, came to realize that physics is to become the leading science. Yet, a revolutionary as he was, he took it into his head to replace Prof. A. D. Goldhammer, dean of the Department of Physics and son of the famous Prof. D. A. Goldhammer, with A. G. Sadreyev, an inventor! <…> A few days later Sadreyev was officially appointed as a dean of the Department of Mathematics and Physics. God almighty! All this "great mind" invented was an electric mousetrap and an idea to use electricity from lightning to power up the first Five-Year Plan[3]. He barely had the smarts to calculate cost per lightning strike (seven copecks as of late 1920s in Kazan). <…> How is it that in the "godforsaken Tsarist Russia" Lobachevsky, a mathematical genius, was appointed rector of the University, and in the post-Revolution Russia a good-natured, simple, working man became a laughingstock for the sake of playing democracy? Oh, right! That is a sacrificial offering to the new God – Ideology <…>.

I was called into the rector's office, where he informed me with delight about his encounter (at a comfort station at Narcompros[4]) with a very distinguished man, who called himself K. N. Shaposhnikov[5], a professor of physics. K. N. Shaposhnikov briefly explained how eager he was to go to Kazan, and Vexlin immediately counted his blessings. <…> The rector appointed Prof. K. N. Shaposhnikov as a dean of the Department of Physics. <…> It did not take long before Shaposhnikov began lecturing first-year students on general physics and spoke at the meeting of the University Society for Mathematics and Physics. As I knew what the speech was to be about, I advised Prof. P. A. Shirokov against attending the meeting, but he had a habit of learning from experience and came anyway. Ten minutes into the speech, the lector dismissed the theory of relativity, and Shirokov whispered in my ear: "I have never thought I will live to see the University has been disgraced that much, with professor of physics denying the theory of relativity". The lectures he gave to his students were little different from the above-mentioned speech, but in them he was, for the most part, telling jokes (sometimes sharp ones) and recounting his accomplishments in science."

Zavoisky appeared to be *de facto* the most accomplished among the physicists at the University. His innate sense of responsibility made him to compensate for the lack of support on the part of his superiors by his own health: he worked with all his might performing scientific research and teaching students. On the top of that, by mid-1930s he was put in charge of a research laboratory set up by the University to study ultra-short waves. "The idea of the laboratory came out of the impression some of the "wondrous" properties of ultra-short waves produced. I was called into the Kuibyshev's office at the People's Commissariat of the Workers' and Peasant's Inspection[6] (he is V. Kuibyshev's[7] brother). When in the building on Il'yinka Street, I was escorted to an office behind two padded doors by some men in military tunics and galliffet[8] trousers with hidden revolvers bulging out of their behinds. There was a man sitting behind the desk, reclined leisurely, heavyset and sleek, and a military man standing nearby. I was asked, point-blank, whether the ultra-short waves can kill from a distance. I answered, that they could not, and I stood my ground. They lost interest in me right away and bade me farewell: we will support the laboratory, but bear in mind, the question asked is of utmost importance! And I then thought: that is what they do at the Workers' and Peasant's Inspection, where I have never met a single worker or a peasant!" (cit. ex. [3])

Late in the 1930s, Evgeny Konstantinovich came within a hair's breadth of his life being destroyed. Over a span of two years, in 1937-1938, Zavoisky's elder brother and his wife, as well as his brother-in-law were all arrested. His younger siblings, a brother and a sister, left the University of their own accord, to stay out of harm's way. Zavoisky himself was all but accused of fascist propaganda for demonstrating Airy's spirals (an optical phenomenon observed in biaxial minerals manifested as light interference patterns of the same shape as swastika) in the lectures on optical crystallography. Committees, one after another, were "zealously, through a magnifying glass, investigating crystals in their quest for a swastika hidden inside, but to no avail, it was not there to be found" [3]. This preposterous incident prompted Zavoisky to turn in his resignation, but administration did not accept it.

[3] Five-Year Plans – a method of planning economic growth over limited periods, through the use of quotas, used first in the Soviet Union and later in other socialist states.

[4] People's Commissariat for Education, an antecedent of the later Ministry of Education.

[5] Not to be confused with I.G. Shaposhnikov, Dean of the Department of Theoretical Physics at The Kazan State University in 1939-1941 and in 1946-1948, referred to in Chapter III: First Decades in the Soviet Union Following the Discovery of Magnetic Resonances in Matter.

[6] A state authority in the Soviet Union with functions similar to those of Russia's present day Audit Chamber and Ministry of Labor.

[7] Valerian Kuibyshev, a high-ranking party official, member of the Politburo of the Communist Party of the Soviet Union and a counselor for economic affairs to Joseph Stalin.

[8] A style of trousers in the Soviet Army uniform: similar to riding breeches, fitting the knees and below and expanding from above the knees.

Fig. 3. Left to right: S. A. Altshuler, E. K. Zavoisky, B. M. Kozyrev. Kazan, 1968. Source: N. E. Zavoiskaya's personal archive.

Evgeny Konstantinovich married Vera Konstantinovna Trufanova. The family's day-to-day living was anything but simple. In 1936, they lost their first-born daughter to a decease.

Since 1933 Zavoisky had been working together with B. M. Kozyrev, a physical chemist. In 1935, he found another longtime associate in S. A. Altshuler (Fig. 3), a brilliant physicist who will carry on Zavoisky's lifework. At the time, Altshuler was newly appointed as an Associate Professor (Docent), Department of Mathematics and Physics, upon finishing his postgraduate research program under the tutelage of I. E. Tamm.

Meanwhile, in 1939, results of the I. Rabi's fruitful research on nuclear magnetic resonance in molecular beams were published [4]. Both Zavoisky and Altshuler developed a strong interest in the subject, as both had previously performed experiments with resonance phenomena of their own: Zavoisky, by that time, had invented a highly sensitive method for studying radio frequency resonance absorption, and Altshuler had just defended his postgraduate thesis on the theory of nuclear magnetic moments. Kozyrev shared their enthusiasm. The three physicists were determined to detect resonance of nuclear magnetic moments in matter rather than in molecular beams, the latter essentially being an ordinary task inconvenienced by the need for a cumbersome vacuum apparatus. To generate a magnetic field, they used a small du Bois–Reymond-type electromagnet with a horseshoe-shaped yoke and rather narrow air-gap of no more than 4 to 5 cm (1.5 to 1.9 in) in diameter and 3 to 4 cm (1.2 to 1.6 in) in length (Fig. 4). At the same time, the "grid-current" method (when absorption is measured by the changes of the grid current of a vacuum tube oscillator) they used to measure resonance absorption, was extraordinarily sensitive for that time. Based on the laboratory notebook records and on their own recollections of the time, Zavoisky's co-authors [5] both later asserted that Evgeny Konstantinovich had been observing nuclear, or proton, magnetic resonance on more than one occasion. Zavoisky performed measurements himself using the frequency range of 6 to 8 MHz in a magnetic field of approximately 1500 G intensity.

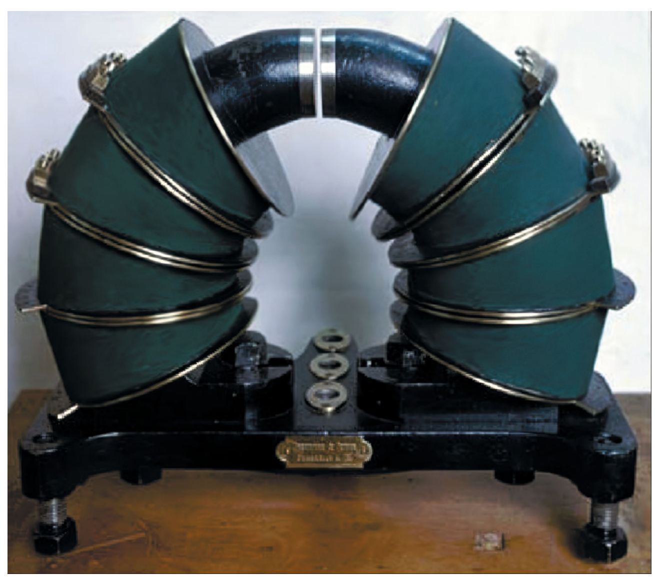


Fig. 4. The du Bois–Reymond-type electromagnet, employed by E. K. Zavoisky, S. A. Altshuler and B. M. Kozyrev in their experiments in late 1930s. Kazan, E. K. Zavoisky Laboratory Museum. Source: I. I. Silkin's personal archive.

It was unclear whether it is at all possible to observe NMR in substances (in “condensed matter”), a circumstance putting considerable psychological pressure on the experimenters. Some theoretical physicists, like Heitler or Teller [6], came as far as to predict that, having absorbed a small amount of energy from electromagnetic field, a spin system would achieve a saturated, i.e., overheated, state. In quantum theory, when a system is saturated, energy levels, which correspond to different orientations of the nuclear spin, hence, of the magnetic moment, are equally populated. C. J. Gorter, a Dutch theoretical and experimental physicist, was already struggling to detect nuclear and electron paramagnetic resonance in matter at the time, but to little avail, as the calorimetric method he used proved to be ineffective in this instance and took his experimentation on the wrong path [7, 8]. Zavoisky came much closer to the discovery. He suggested using the “grid current” method permitting to detect absorption of energy in a paramagnetic substance through the changes in responding behavior of a radio circuit, an approach considered to be the most sensitive up to the present day. The “saturation avenue of exploration” showed promise. Today, it is common knowledge, that there are more than one mechanism for the spin to give off energy to the crystal lattice, all providing sensitivity high enough for the NMR to be observable: spin energy can be converted into kinetic energy of conduction electrons or, in liquids, into thermal motion of molecules, among other possibilities. If only the pioneers were aware of that back then! Later on, after the discovery had been made, with regard to different other research, Evgeny Konstantinovich instructed his colleagues, that once energy is given off to the system, the system would find its way to distribute it among the multiple degrees of freedom.

Phenomena, considered as a clear indication of NMR detected in matter now (with works by Purcell and Bloch published in 1946), were not enough of foundation for the group of physicists at the Kazan University to publish their findings back then. For the reasons unknown at the time, the resonant signal was detected sporadically, depending on a number of random factors, like accidental vibrations of the apparatus. Hence, influence of the magnetic field inhomogeneity applied to the sample was highly inconsistent, unpredictable, and hard to measure. In most cases, spread in the field intensity values, of which resonant frequency was a function, was too wide, and therefore the line width broadened to become undetectable. The du Bois–Reymond-type magnet was not absolutely reliable in terms of its mechanical integrity, while optimum inhomogeneity value in the air gap of this miniature magnet was on itself too big. This circumstance did not permit Zavoisky to announce the discovery, but he was still persistent in his experiments. Meanwhile, in 1945, his American colleagues were “hunting” for NMR in the air gap of a large electromagnet used in a cyclotron to study cosmic rays. The gap was up to 60 to 70 cm (23 to 21 in) in diameter and provided, if compared to Zavoisky’s magnet, two to three orders of magnitude more homogeneous magnetic field within a specimen with a hundred to a thousand times lower spatial dispersion of the magnetic field intensity.

Basically, Bloch and Purcell had only one difficulty to overcome: they needed to find the magnitude of electromagnetic current required for the field to reach the resonance value (it was enough to roughly estimate strength of the field for the cyclotron to work). In the USSR, there were five or six magnets comparable to the one used by the American physicists, but they were all available to only few scientists engaged in a totally different line of research.

The plot thickened as the World War II broke out and interrupted the search for NMR effects in an absolutely ludicrous way. Before the war, the University scientific brainpower was not at its best, while Zavoisky needed accomplished physicists to partake in his experiments. One would think that relocation of the Leningrad Physical-Technical Institute (PTI) of the USSR Academy of Sciences from Leningrad to Kazan would reinforce the research. The reality proved otherwise. For the high commission of academicians and professors of this scientific institution one glance was enough to give the verdict: this primitive device is unfit for scientific purposes. Evgeny Konstantinovich reminisced: the apparatus was dismantled, or, rather, it was destroyed, its owner not present and in opposition to this act of vandalism; in the vacated office, for two years, PTI’s employees had been redeeming their bread ration coupons.

S. I. Altshuler volunteered for the front lines. Zavoisky was redeployed to assist with the defense-related project. On paper, the research pertained to radio location, but *de facto* Zavoisky was compelled to assist V. K. Arkadyev, a corresponding member of the Academy of Sciences, with his rather hopeless research [9]. And yet, Arkadyev’s project was provided with generous financing (“5000 RUB for special work”) and was nominally developed at the P. N. Lebedev Physical Institute (LPI) of the Academy of Sciences [10]. To sustain the University staff amid the famine and chaos of the war, Zavoisky and his colleagues worked in the fields – agricultural allotments the University had to provide for its needs – harvesting crops and firewood. Evgeny Konstantinovich was often in charge of those survival efforts. Institutes of the Academy of Sciences, relocated from Moscow and Leningrad to Kazan, got to occupy a good number of the University’s buildings. One should bear in mind, that this arrangement went far beyond overcrowded premises. All of the buildings belonging to the Kazan University were reallocated to the Academy of Sciences. Only some of them, but mostly offices, sometimes floors in separate buildings, were left at the disposal of the University “to ensure the academic process continued” [11]. At their home, employees of the University were at the mercy of the Academy with very little control over the situation, if any. They were not allowed to the majority of the buildings. At war times, collateral damage is unavoidable. But why destroy a fully functional apparatus!

In 1943, following the Academy’s institutes relocation back where they belonged, Arkad’yev’s laboratory included, Zavoisky resumed his experimental work and insisted on a new research plan to be approved. This time, he meant to study parallel and, most importantly, perpendicular fields absorbing radio-wave energy. Zavoisky suggested placing vials containing paramagnetic salts and salt solutions, as well as metal powders, inside the oscillating circuit induction coil, as there the magnetic component of electromagnetic oscillations was the strongest.

Up to this day, it is an open question as to why Zavoisky’s discovery of EPR did not lead him straightaway to observing NMR as well. The question might seem relevant from today’s perspective only, as phenomena obvious to modern scientists were not known to Zavoisky or to his contemporaries. One of such phenomena is a wide diversity of magnetic resonance manifestations and related research, a reality the today’s experimenters are accustomed to. It is evident now, that the NMR spectroscopy as applied to liquids or solids, organic or inorganic materials, and so on are each a distinct line of research with its own nature and experimental approach. As would be shown later, after Rabi had discovered magnetic resonance phenomenon, it had still to be rediscovered over again in each new substance. There was no clear differentiation between, at the very least, nuclear magnetic, electron paramagnetic, or ferromagnetic resonance experimentation in the times, when the first discoveries were made. In the scientific magazines of those years you can see findings on EPR, NMR, and FMR spectroscopy often published in the same section. Comparing to geographical explorations, a discovery of the South Pole does not imply an expedition should be immediately sent to find the South Magnetic Pole, the Pole of Cold, or the Pole of Inaccessibility. Discovering Antarctica is considered a great endeavor of its own merits with these other “points on the map” gaining explorative interest later.

Another phenomenon affecting modern perspective is the focus on success, awards, and priority rule, characteristic of the present-day science. It would be unreasonable, though, to ascribe motivations common in the 21st century to the pioneers of magnetic resonance making history in the 20th century. It is hard to imagine Zavoisky being driven by the urge to win the race for all possible resonance phenomena, when performing his experimental work. Meanwhile, his discovery of EPR opened up as much new avenues for research as any other, though hypothetical at the time, resonance phenomenon would.

Indeed, Zavoisky’s very first experiments with paramagnetic substances showed much promise. In the period of late 1943-early 1944, experiments were performed sporadically, a casualty of the war. Yet, it was in those years that, in his notebooks, he first mentioned resonances for the fields of the order of 12 Oe and excitation frequency of the order of 35 MHz, detected with a radio-frequency coil aligned perpendicular to the constant magnetic field. To generate constant field Zavoisky used two identical circular magnetic coils placed symmetrically along a common axis, a Hemholtz pair (Fig. 5), instead of the magnet he had previously employed. Radio-frequency constantly increased, the resonance appeared at approximately several dozen megahertz in the magnetic fields of two to three dozen gauss [9].

The scheme allowed for the current in the coils to be modified repeatedly by means of sawtooth voltage supply. With a low-frequency sinusoidally modulated field added to the constant field, sensitivity of the method grew dozens of times higher. The device allowed for an audio-frequency oscillator to be connected to the Hemholtz coils via the capacitors and in parallel with the storage battery, a DC power source, to obtain a low-frequency signal (resulting from demodulation of the oscillator signal), which was ready to be filtered out of noise.

Reproducibility, that is repeatability of the results, was strong enough this time with the laboratory notebook entries on resonances recurring repeatedly. A simple calculation showed that for some of copper, manganese, and chromium salts maximum of absorption corresponded to the resonance of the magnetic moment, which was close or even identical to the magnetic moment of the free electron. The most telling was position of the peak in the absorption curve $A (H)$, sawtooth current I fed to the coil, in which A was the signal intensity as registered by the recorder and $H = kl$ was the magnetic field intensity (Fig. 6). The curve was plotted point by point by means of a galvanometer or on the moving film of the cathode-ray oscillograph with the Hemholtz coils direct current, i.e., field intensity, slowly changing. The calculation definitively demonstrated that the phenomenon observed was a resonance absorption of the energy from electromagnetic oscillations by the electron magnetic moments of a transition metal (copper, manganese and chromium) ions contained

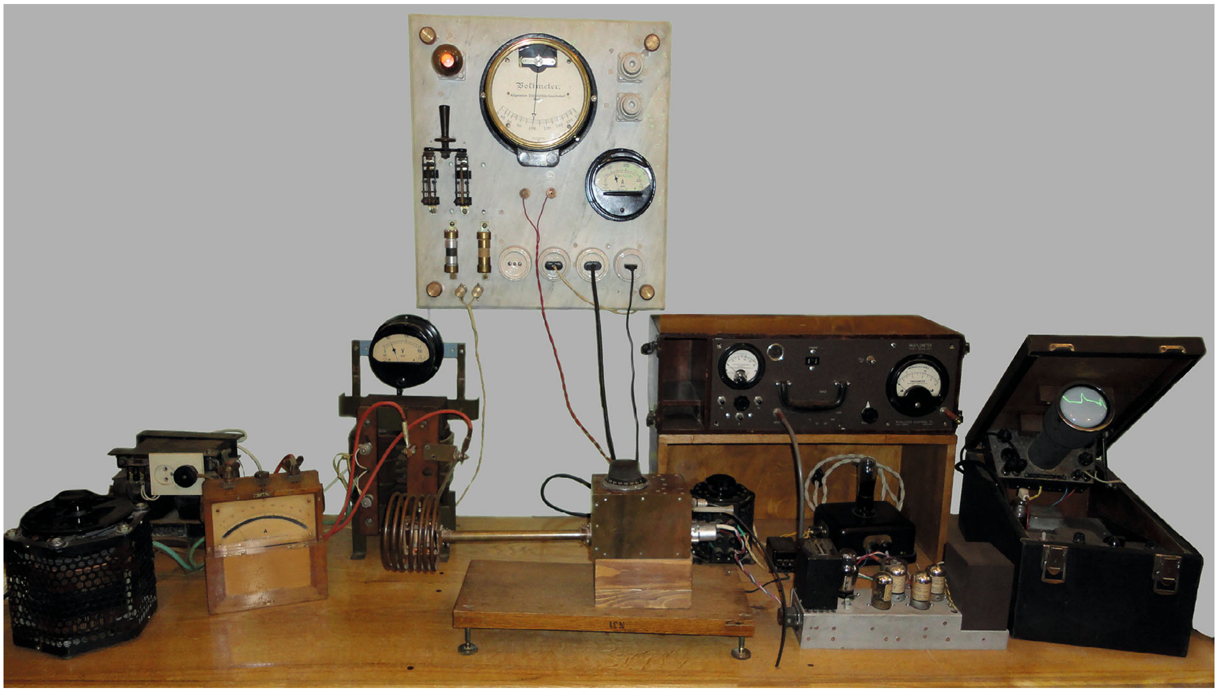
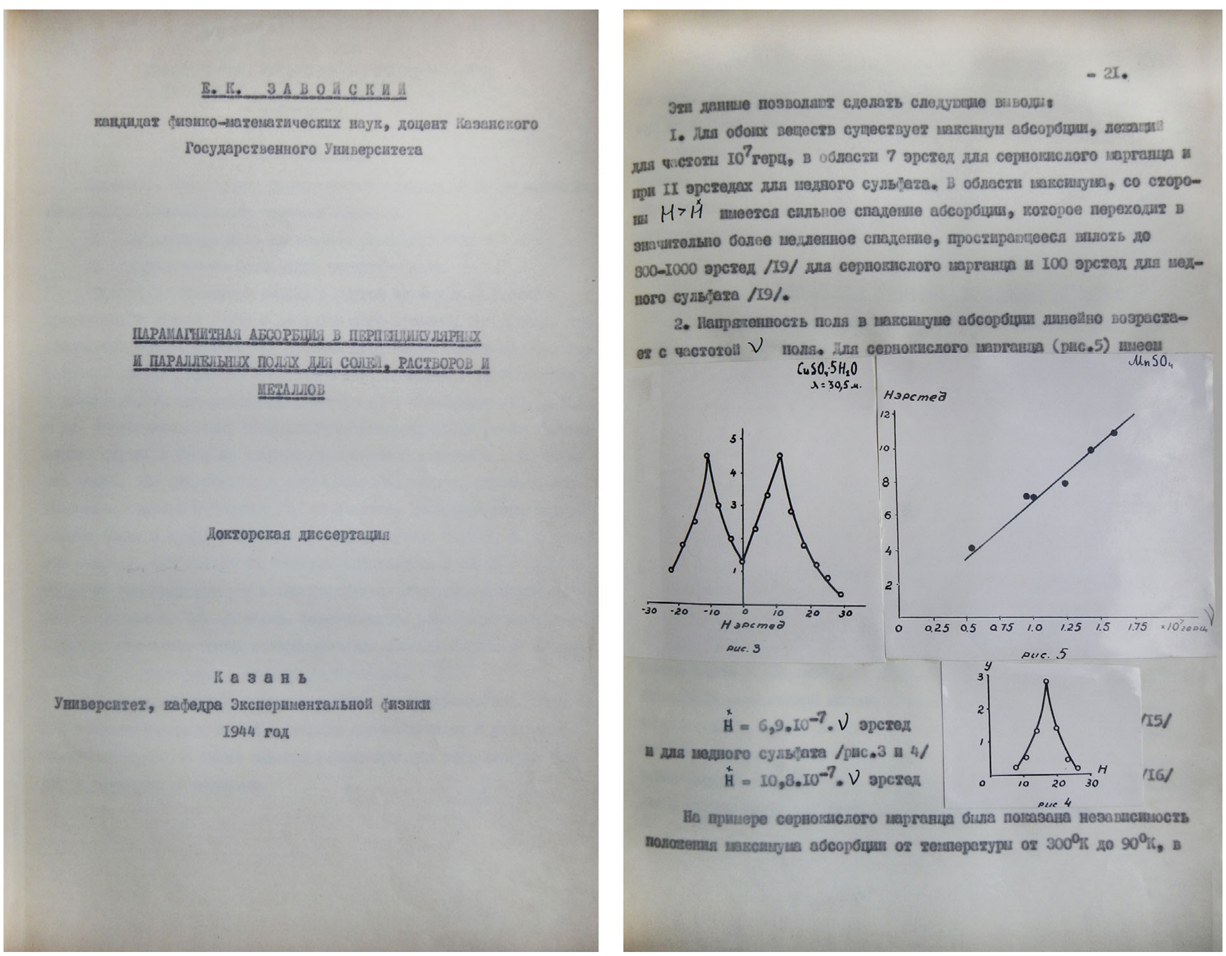


Fig. 5. The apparatus by means of which E. K. Zavoisky observed EPR for the first time ever, as reconstructed by I. I. Silkin. Kazan, E. K. Zavoisky Laboratory Museum. Source: I. I. Silkin's personal archive.



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ПАРАМАГНИТНАЯ АБСОРБЦИЯ В ПЕРПЕНДИКУЛЯРНЫХ И ПАРАЛЛЕЛЬНЫХ ПОЛЯХ ДЛЯ СОЛЕЙ, РАСТВОРОВ И МЕТАЛЛОВ

Докторская диссертация

К а з а н ь

Университет, кафедра Экспериментальной физики

1944 год

- 21.

Эти данные позволяют сделать следующие выводы:

1. Для обоих веществ существует максимум абсорбции, лежащий для частоты 10^7 герц, в области 7 эрстед для сернокислого марганца и при 11 эрстедах для медного сульфата. В области максимума, со стороны $H > \overset{*}{H}$ имеется сильное спадение абсорбции, которое переходит в значительно более медленное спадение, простирающееся вплоть до 800–1000 эрстед /19/ для сернокислого марганца и 100 эрстед для медного сульфата /19/.

2. Напряженность поля в максимуме абсорбции линейно возрастает с частотой ν поля. Для сернокислого марганца (рис.5) имеем

$$\overset{*}{H} = 6{,}9 \cdot 10^{-7} \cdot \nu \text{ эрстед} \qquad /15/$$

и для медного сульфата /рис.3 и 4/

$$\overset{*}{H} = 10{,}8 \cdot 10^{-7} \cdot \nu \text{ эрстед} \qquad /16/$$

На примере сернокислого марганца была показана независимость положения максимума абсорбции от температуры от 300°K до 90°K, в

Fig. 6. Title page and one of the pages of E. K. Zavoisky's doctoral dissertation. Source: V. V. Ptushenko's personal archive.

in their salts. The spectroscopic factor *g*, or *g*-factor as it is known today, of a free electron (its magnetic moment equal to 1 Bohr magneton or β) is almost 2. Zavoisky's experiments showed the *g*-factor, indeed, approximating 2. With the frequency *f* being changed, the peak position shifted proportional to the change in the excitation frequency for the maximum of *A* to be obtained once the condition $f = (g\beta/h)H_{max}$ was met, in which *h* was the Planck's constant.

In the Zavoisky's first experiments, the spectral line, an essential EPR attribute, at the coordinates of *A (H)* was broad enough for non-negligible absorption in the low-frequency alternating magnetic field to remain far from the resonant field H_{max} (for example, both at $H = 0$ and at $H = 2\ H_{max}$). In May 1944, having finalized the first stage of his research, Evgeny Konstantinovich submitted his doctoral dissertation to the Physical Institute of the USSR Academy of Sciences, Moscow (Fig. 6).

Zavoisky did his experimental work in the circumstances hard to survive in, let alone to advance the science. His major competition in the magnetic resonance research, C. J. Gorter, lamented that the situation in the Netherlands occupied by Nazis made it extremely difficult to perform experimental research. Unbeknownst to Gorter at the time (most likely the Dutch physicist came to know of the Zavoisky's work not before 1945), his colleague in the war-time Kazan continued his experimentation in between managing the University's subsistence farm, cultivating the family's kitchen garden, and hunting for rooks (for food). To assemble his new apparatus Zavoisky had to procure parts himself or with the help of his students, employed in the defense industry, his prior association with the radio location project being of no help. In his memoirs (published after his death), Zavoisky reminisced about how hard it was to get hold of every piece of equipment [12]. In 1943, Evgeny Konstantinovich returned to teaching as well.

Ya. I. Frenkel (Fig. 7), the USSR's most renowned theoretical physicist and head of the Department of Theoretical Physics at the Leningrad Physical-Technical Institute, was the first to develop interest in the discovery of EPR and to give it a theoretical formulation [13]. He definitively confirmed the nature of the observed phenomenon as an electron spin resonance. His interpretation of the resonance line shape, though, was rather formalistic. Yet, his endeavor facilitated acknowledgment of the Zavoisky's work by the scientific community.

In 1944-1945, Evgeny Konstantinovich was a frequent visitor to Moscow, defense of his dissertation continuously deferred. Some of academicians, scientific elite, no less, remained largely skeptical of it being possible for a little-known physicist to observe such a fine phenomenon, as perceived back then,

Fig. 7. Ya. I. Frenkel. Source: The Free Encyclopedia; URL: https://fr.wikipedia.org/wiki/Yakov_Frenkel.

all by himself and in the direst of circumstances. Optical physicists doubted it was within the realm of possibility to directly observe such low-energy quantum absorption. This quantum phenomenon in the Zavoisky's experiment corresponded to the *Zeeman effect*, or hyperfine splitting of a spectral line, and it was known to be observable in optical spectra of vapors or gases placed in a magnetic field. "Professional naysayers" were in abundance too, they always are, rejecting all that was created by the minds other than from Harvard, Oxford, Berkeley or, if nothing else, from Leningrad Physical-Technical Institute, Lebedev Physical Institute, or Kharkiv Institute of Physics and Technology.

Help came from the Soviet Institute for Physical Problems (IPP), namely from Peter Kapitsa and Aleksander Shalnikov (Figs. 8 and 9). To address the doubts, they invited Zavoisky to the IPP to reproduce his experiments using vast resources the Institute could offer. He was now able to replicate his experimentation, firstly, in the higher frequency range of up to 2.75 GHz, corresponding to higher fields of up to 1200 Oe; and secondly, over a wider range of temperature, with liquid hydrogen temperature at −253°C or 20 K. Next, he reproduced the experiment using the boil-off vapors from liquid helium as a coolant, thus obtaining the temperature of −269°C or 4.2 K. Shalnikov, a virtuoso experimenter, assisted Zavoisky in person and was astonished by the extraordinary sensitivity of this method. The apparatus was assembled and given a test run in January of 1945, within a couple of weeks! The EPR phenomenon in the same substances Zavoisky investigated in Kazan was

Fig. 8. Left to right: L. A. Artsimovich, M. A. Lavrentyev, N. N. Semenov, P. L. Kapitsa. 1956. Source: Peter Kapitsa Memorial Museum of the Institute for Physical Problems. Provided by T. I. Balakhovskaya.

Fig. 9. Standing (left to right): A. I. Alikhanov, P. Savich; seated (left to right): A. I. Shalnikov, L. D. Landau. Moscow, Institute for Physical Problems, 1946. Source: N. A. Shalnikova's personal archive.

officially confirmed, all skeptics were proven wrong. Supported by Ya. I. Frenkel, Zavoisky, finally, defended his doctoral dissertation[9], with E. I. Kondorsky and A. I. Shalnikov participating in the capacity of dissertation opponents.

Unfortunately, official acknowledgement of the discovery brought about only little improvement, if any, to the Zavoisky's working environment, or to his living circumstances, for that matter. On the bright side, Semen Alexandrovich Altshuler, a close associate of him, came back from the front lines of war. Together, the three of them, Altshuler, Kozyrev, and Zavoisky, soon determined the mechanism behind the broadened profile of spectral lines. They attributed the phenomenon to interaction between the magnetic moments of unpaired electrons in paramagnetic salts. In 1947, having no knowledge of the James Griffiths's recent discovery, Zavoisky detected ferromagnetic resonance. Evgeny Konstantinovich was formally offered his own laboratory at the recently re-established Kazan Physical-Technical Institute of the Academy of Sciences (in 1984 named after E. K. Zavoisky). Yet, the provided financing was negligible. The letter, dated November 11, 1946, he and his colleagues, I. G. Shaposhnikov, S. A. Altshuler, and B. M. Kozyrev, wrote to S. I. Vavilov, president of the Academy of Sciences, was most illustrative of the circumstances he had to grapple with in those years. In the letter, the accomplished scientists asked Vavilov for assistance with procuring an electromagnet, essential for carrying out further research on electron and, more importantly, nuclear magnetic resonance. Official requests for a magnet, or at the very least for the components to assemble it with, submitted to both local authorities and to the Academy of Sciences had all proven unhelpful (published in: [9]). Meanwhile, by the end of the year 1946, nuclear magnetic resonance had already been discovered, its potential for further scientific advancements was obvious enough for the physicists in the West to start massively researching the relating phenomena [14, 15].

The Zavoiskys lived in two storage rooms somewhat redesigned to serve as living quarters. Heat coming from a potbelly stove barely lasted for a couple of hours with the opposite wall being freezingly cold all the time. Zavoisky's wife and daughter were both ill, and his home was absolutely unfit for any serious work. The University administration refused to help the esteemed scientist to improve his living conditions, as his situation was referred to in the official documents. Altshuler reminisced, that the post-war hardship was not blame, rather it was the attitude on the part of the University's rector, K. P. Sitnikov, for whom Zavoisky's integrity was hard to put up with ([16]). Meanwhile, dissertation Evgeny Konstantinovich had recently defended draw some serious attention. News of a gifted experimenter reached I. V. Kurchatov, head of the Soviet nuclear program. In 1947, he suggested that Zavoisky should join his research team.

According to the memoirs of his colleagues at the nuclear research laboratory, Zavoisky was assigned the task of calculating shockwave (initiated by the chemical explosion) velocity enough to compress the subcritical sphere of a fissile material in the atomic bomb into a supercritical mass. In his experimentation, Evgeny Konstantinovich employed electromagnetic methods, his research being one of

[9] The transcript of the defense was published almost in its entirety in the book by N. E. Zavoiskaya [26].

the several with the same goal carried out simultaneously. Zavoisky appreciated complexity of the project he was assigned to, but felt profoundly uncomfortable about the ultimate goal of the nuclear program. The family moved to Moscow, where he was finally offered a decent apartment, while Evgeny Konstantinovich left for Arzamas-16, now Sarov, to join the nuclear program. His daughter reminisced: “That was a dark period of my father’s life. I was too young at the time to comprehend the high price he had to pay for our family’s well-being. He did not like revisiting those painful years, neither was he allowed to, as his work was classified. In February 1949, he wrote to my mother, who was giving birth to their son at a maternity hospital “… I would not like him to become a physicist: this science grows increasingly despicable, he would be much better to engage in human physiology or astronomy” [17]. In 1951, Zavoisky, at long last, managed to break away from Arzamas-16 and from atomic weapons development, something he had been asking Kurchatov for. From then on, for many years, he had been working at the Laboratory of Measuring Instruments of the USSR Academy of Sciences, several years later changing its name to the Institute of Atomic Energy (IAE) and ultimately named after I. V. Kurchatov.

In seven years Zavoisky did not published a single paper. For seven years he had been working hard together with a large team of physicists and engineers to create spin-polarized atomic beams, an unrewarding, yet necessary process. In 1956, a source for spin-polarized protons and deuterons was developed.

In parallel, Evgeny Konstantinovich had been developing experimental methods for studying ultrafast processes, a certain follow-up to his work in the Soviet nuclear program. In 1953, Zavoisky was elected a Corresponding Member the Academy of Sciences of the Soviet Union.

His experimental work on the nuclear project showed, however, that his electromagnetic method, with the equipment available, was not the most effective for studying shockwave propagation. Soon afterwards, Zavoisky set out to study electrical discharges. To that end, together with S. D. Fanchenko he designed a multi-stage cascaded optoelectronic converter. At every stage of the cascade there was a photocathode (a cathode emitting electrons when struck by light) and a compact linear accelerator with an output phosphor screen. When hitting the phosphor screen, an accelerated electron produced a brighter than originally flash of light. Skillful experimenters, Zavoisky and Fanchenko used simultaneously five to six of such cascaded stages with time-dependent light pulses remaining largely undistorted. The optoelectronic converter allowed for the electron image to be analyzed in time and scanned in space. Zavoisky also designed a new method for detecting ionizing particles, which he named a scintillation chamber [18].

Evgeny Konstantinovich together with M. M. Butslov and colleagues made some significant improvements to the design of a multi-stage high-resolution time-analyzing image intensifier tube. The enhanced scheme permitted observing processes with 10^{-14} s time resolution. The new apparatus, for example, helped to establish that the glow phase in the miniature spark discharges may last for as little as 10^{-10} s, a thousand times less than it had initially been believed. This finding was at the root of using optoelectronic converters for counting charged particles. Cascaded multi-stage optoelectronic converters found numerous applications in studying laser pulses, in astronomy, in high-speed photography of matter shock disintegration process, etc. [19].

It is worth noting here, that Zavoisky was among the first laureates of the Lenin Prize, when it was re-established in the USSR in 1957. He was awarded the Prize for his discovery of electron paramagnetic resonance, a decision welcomed enthusiastically by the great majority of the Soviet scientific community. Evgeny Konstantinovich, an outstanding experimenter and a wonderful, considerate, and principled person, was widely respected and loved.

In 1957, Zavoisky focused efforts on investigating plasma phenomena. Among other things, his research team worked to achieve controlled nuclear fusion reaction. Numerous problems stood in the way, one of them there being absence of an obvious method for pumping energy into plasma to heat it. As a possible solution, Zavoisky suggested using magneto-acoustic resonance manifesting itself when the frequency of magnetic field oscillations coincided with the one of many frequencies of the charged particle self-oscillations in a plasma. He thus discovered a complex and multifaceted phenomenon of turbulent heating characterized by the transfer of energy between the regular oscillations and chaotic oscillations of the charged particles or charged-particle bunches. This particular research project proved to be a strong start for a good many prominent experimental physicists, like A. P. Akhmatov and M. B. Babykin to name a few. L. I. Rudakov, soon to be a renowned theoretical physicist, was also on the Zavoisky’s team.

In 1964, Evgeny Konstantinovich was elected a full member of the USSR Academy of Sciences, breakthrough results his research team delivered were recognized. In that period, Zavoisky set directions for the advances in plasma physics in the USSR and beyond, across the Soviet bloc. His vision of this branch of physics development included, among many other things, establishing an Institute for Hot Plasma Physics in the USSR, an idea that found little support, however. In 1967, he proposed that the Soviet and Czech physicists should join their scientific efforts, the latter being at the cutting edge of plasma research at the time. Thwarted by the turmoil of the Prague Spring, 1968, though, this cooperation never happened.

In 1967, Evgeny Zavoisky was cut off all communication with his colleagues in the West for reasons still unclear. Only thrice in 20 years had he been allowed out of the country, despite invitations to the prestige international conferences, both on electron paramagnetic resonance and on plasma physics, extended to him on a regular basis. Meanwhile, other USSR scientists of the comparable caliber and repute were much more frequent participants on the international stage. His classified work for the Soviet nuclear project in the 1940s can hardly be blamed, as his Arzamas-16 colleagues suffered no such obstacles. Frustratingly, on quite a number of occasions, Zavoisky was authorized to accept an invitation and speak at a conference outside the country only to be informed days before the departure, all of a sudden and after months of preparation, that the decision had been reconsidered, his trip cancelled. Three times only he delivered his paper in person: in 1961, Salzburg, Austria, in 1965, Culham, Great Britain, and in 1967, Prague, Czechoslovakia.

A scientist of overwhelming, prominent talent, many would say a genius, Evgeny Konstantinovich unraveled puzzles never approached before, at times much to annoyance of some of his colleagues and rivals – such an observation was shared by G. A. Askaryan [20], who knew Zavoisky well through the plasma research. Zavoisky treated all his colleagues with unvarying kindness and respect, without exception. He was a true intellectual, a living example of devotion to Truth and to Science. “Some researchers joked, that Zavoisky was the only academician at the Institute who indeed worked there” [21]. An episode, R. A. Antonova related in her reminiscences about Evgeny Konstantinovich, would me the most descriptive of him:

“It was mid-1960s. G. I. Rostomashvili and I came to the I. V. Kurchatov IAE to get to know some of the methods used by Evgeny Konstantinovich and his team in plasma experimentation, and to discuss our research. <…> We were warmly welcomed into his laboratory and were given directions to the office Evgeny Konstantinovich worked in. We felt awfully shy of meeting the “father of paramagnetic resonance”. We knocked slightly on the door. Someone invited us in. Once inside, we found ourselves in a laboratory room rather than in an academician’s office, as one would expect. Busy with one of the apparatuses, the only person in the room was a middle-aged experimenter, dressed in a black laboratory gown, a soldering iron in his hand. He was re-soldering together some pieces of a scheme. We immediately felt at ease and asked simply where to find academician Zavoisky. His astounding reply took us aback: “I am listening”. We were speechless with astonishment. Evgeny Konstantinovich put aside his soldering iron and looked at us, his eyes slightly squinted, kind, and tranquil.” [22]

In his last years, Zavoisky experimented with relativistic electron beams, i.e., streams of electrons moving with the speed comparable to that of light, as a method for igniting fusion. Also, in those years he approached the problem of high-temperature superconductivity.

His last years, regrettably, were full of hindrances impeding his life and work. As mentioned above, he was repeatedly denied international speaking opportunities in quite unceremonious manner, at the eleventh hour. He thus never got to speak at the conferences in Japan, in 1970, and in the USA, in 1971. Uncannily refused the right to travel the day he was due to get his papers at the State Committee on the Utilization of Atomic Energy, Evgeny Konstantinovich, no doubt, felt deeply insulted. When he came to collect his papers for the trip to the US, he was not allowed inside the office, no explanation offered. In the eyes of a bureaucrat, an ordinary Soviet man, obviously, knew no other attitude. “Why are you here? You are not going anywhere,” so much for explanation. Someone decided that Evgeny Konstantinovich must not travel abroad. Most importantly, no one in the IAE management would not or failed to, at best, to defend the right of the Institute’s most prominent scientist to deliver his papers to his colleagues at the international stage in person. After one of such incidents, Zavoisky, 64, resigned. Straggling to grasp the motive behind, some of his colleagues attributed his unexpected resignation, at the very peak of his career, to the persistent refusals to his requests for permission to travel abroad. G. A. Askaryan, for example, believed, according to his reminiscences, that Zavoisky thus protested against violation of his individual rights. The reality was far more complex, though: Evgeny Konstantinovich was repeatedly refused not only to travel to present papers by the State Committee, but, most importantly, he was repeatedly refused financing by the Institute. Basically, at the IAE, with full-scale research on the controlled thermonuclear synthesis launched and generously financed, Zavoisky’s laboratory struggled to get financing essential for any serious experiment to be carried out. Many years later, V. L. Ginzburg recounted his conversations with Evgeny Konstantinovich: “We both were completely candid. He should not have left the Institute. He could have carried on working. Artsimovich resorted to playing dirty tricks against him? So what? He should have carried on working.

He had pride. I do not have pride, you know. I cannot afford pride" [23]. If Zavoisky would be a theoretical physicist he could have indeed "carried on working". Yet, he was an experimenter. The outdated apparatus he had at his disposal exhausted its capacity for producing data for new research, assembling of a new one was put on hold indefinitely. Zavoisky literally had no options left, apart from moving focus to a different field. Basically, he found himself trapped in a situation very similar to his circumstances in 1947. This time, however, he had nowhere to go. Kurchatov, who made a difference back then and whom Evgeny Konstantinovich, by accounts of many, respected deeply, had passed away. Denied essential resources to continue his work, Zavoisky left the Institute. He was 64, in the prime of a true scientist's life.

In 1972, after he had retired, Evgeny Konstantinovich suffered a severe heart attack. A man of honor, Zavoisky, still in recovery, was one of the few ready to come to the defense of Andrey Sakharov in 1973, when the latter became the target of official censure and harassment. His poor health, however, did not allow him to do much. In that period, Evgeny Konstantinovich finished writing his reminiscences about the Kazan University and some of his colleagues. He never stopped working on the new ideas in plasma physics, although, retired, it was harder to get them published. In his last year, Zavoisky worked as Editor-in-Chief for the *Advances in Physical Sciences* magazine (*Physics-Uspekhi*). Like with everything he ever did, he took this last commitment seriously, devoting much of his time and intellect to the job. As ever, his personality and attitude made lasting impression upon his co-workers. L. I. Kopeykina [24], managing editor at the *Advances in Physical Sciences* thus reminisced about her experience of working with Zavoisky:

"I remember meeting Evgeny Konstantinovich. It was April, 1976, soon after the Presidium of the Academy of Sciences appointed him as an Editor-in-Chief. I was in the editorial office, when I heard someone knock on the door delicately, and then a man came in, of short stature, his hair streaked with gray, his eyes radiating kindness, with an element of shyness about him. He greeted me politely. I offered him a seat. He took a seat and said: "I am Zavoisky." At first, it felt awkward <…> I expected the new Editor-in-Chief to ask the staff to his home office to meet him. Evgeny Konstantinovich, however, made it clear right away, that he would prefer to meet with the staff at the editorial office to prevent visitors from finding the doors closed during office hours and to make sure they can always get assistance they came for.

His attitude stunned me: he was a prominent scientist, an academician, his schedule always tight, he was advanced in his years, his health failing him, and, on top of that, he lived a long way from the editorial office. What amazed me most, though, was his kind and caring manner, his respect for other people's time.

Business matters were discussed last. Evgeny Konstantinovich first got acquainted with the editorial staff, wages, and responsibilities of each and every member of the team, and only after that he delved into the day-to-day matters of the editorial office." [24]

On October 10, 1976, Evgeny Zavoisky, 69, passed away.

Throughout his life, after 1953, Evgeny Konstantinovich never severed his longstanding friendly or scientific ties with his fellow physicists at the Kazan University or with many Soviet scientists sharing his interest in magnetic resonance. Appointed by the Academy of Sciences, Zavoisky oversaw development of the Kazan Physical-Technical Institute. Among other things, he facilitated constructing its new building at the Siberian Route (Sibirsky Trakt).

In 1969, an international conference took place in Kazan to mark 25th anniversary of the EPR discovery, an important milestone for the entire magnetic-resonance community. Zavoisky, one of the key persons in the history of this discovery, was highly praised for his pioneering work on the phenomenon by Cornelis Gorter and Alfred Kastler, a Noble Prize laureate "for the discovery and development of optical methods for studying Hertzian resonances in atoms", both speaking in Kazan. Alfred Kastler ended his speech by saying: "Dear colleagues! As our plane approached the Kazan airport, it flew over the Volga River. For us, to see this river with our own eyes was emotionally overwhelming. Beginning from a small spring, The Volga then grows wider and wider, until it becomes a mighty river, deep as an ocean. So does paramagnetic resonance. It began from a small experiment, performed here, in Kazan, 25 years ago. Now that the years have passed it became a vast scientific field, rich in research and papers…" [25]

Zavoisky, in his speech, offered his ideas on two promising, groundbreaking experiments on magnetic resonance.

As the scientific community bid its final farewell to the late father of EPR, the question "Why was not Zavoisky ever given the Nobel Prize for his discovery?" bewildering many of his colleagues across the world loomed large, prompting the search for the answer. N. E. Zavoiskaya, daughter of Evgeny Zavoisky, collected a huge amount of first-hand accounts to get at least some understanding [26]. S. A. Altshuler and B. M. Kozyrev [5, 27, 28], as well as many other scientists, presented their thoughts and evidence in their contributions to the "Magician of Experiment" volume, a collection of essays, published to commemorate Zavoisky. So did S. V. Vonsovsky, a patriarch of the Soviet magnetism research, who, in association with Cornelius Gorter, the Netherlands, and Ivar Waller, a Swedish theoretical physicist and the author of the first theory of paramagnetic relaxation, nominated E. K. Zavoisky to the Nobel Prize. V. L. Ginzburg [29] also wrote about his nominating Zavoisky to the Nobel Prize. The Nobel Prize history of magnetic resonance is recounted in more detail in the next section. At the international conference, held in Heidelberg, Germany, in 1976, the Prize Committee of the International Society for Magnetic Resonance (ISMAR) decided to award the ISAR Prize for the year 1977 to Evgeny Zavoisky. Sadly, the Award was given to him posthumously.

In 1991, the International Zavoisky Award was established to recognize outstanding research and developments in the field of electron paramagnetic resonance. The idea of the Award was suggested by Professor K. M. Salikhov, head of the Kazan Physical-Technical Institute. The Zavoisky Award is presented every year in September, in Kazan, celebrating birthday anniversary of the EPR discoverer. Among the scientists, who received the Zavoisky Award, there are internationally recognized experts on EPR-spectroscopy, such as William Mims, USA; Brebis Bleaney, UK; Yakov Lebedev, Russia; Klaus Moebius, Germany; James Norris, USA; James Hyde, USA; George Feyer, USA; and Kamil Valiev, Russia.

E. M. PURCELL: LIFE AND SCIENTIFIC JOURNEY

The obituary in the New York Times [30] paid tribute to Edward M. Purcell as a person “who made it possible to “listen” to the whisperings of hydrogen throughout the universe”, the fact of him sharing the Nobel Prize in Physics “for discovering a way to detect the extremely weak magnetism of the atomic nucleus” made reference to in a later paragraph. (see Fig. 10).

Best known for his two “fundamental discoveries” [31] – the discovery of NMR absorption and the detection of the emission of radiation at 1421 MHz by atomic hydrogen in the interstellar medium – each leading “to an extraordinary range of developments” in atomic, molecular and nuclear physics, chemistry, medicine and radio astronomy, Purcell made “ingenious contributions” in biophysics and astronomy, and “set a new standard of scholarship” in his Berkley Course introductory textbook on electricity and magnetism.

Anatole Abragam, a Russian born French physicist held in high regard by his Soviet colleagues, who knew Purcell well, greatly appreciated his personality and professionalism. He wrote [32]: “As a physicist and a human being Ed Purcell is perhaps the man I admire the most. I have never met anyone more profoundly authentic, more detached from the wish to appear other than he is.”

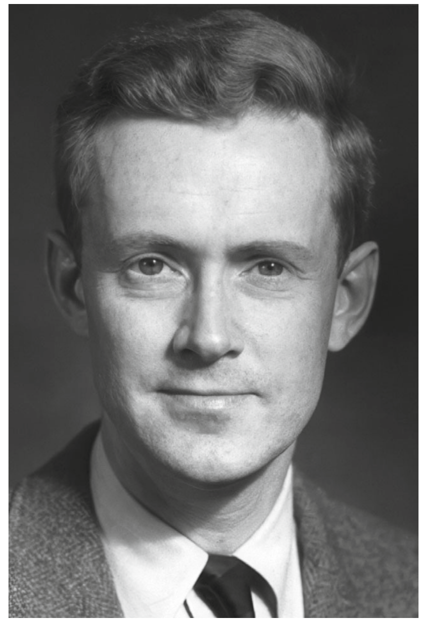

Fig. 10. E. M. Purcell. Source: The Free Encyclopedia; URL: https://en.wikipedia.org/wiki/Edward_Mills_Purcell.

In his autobiography [32] he compared Purcell to Andrey Sakharov. Once you remember how in 1965 he resigned from the President ’s Science Advisory Committee in protest against the continuing war in Vietnam, this parallel between the two great men comes out ever more convincing.

Below is a brief account of the life and scientific path of Edward Purcell, an outstanding scientist, an indefatigable researcher, a brilliant teacher and a visionary, any scientific project was lucky to have at its team. Facts of his life and his personal attitudes have been preserved for future generations in his interviews and in reminiscences of his close associates (for example, [31]), courtesy of the efforts from his colleagues at the American Institute of Physics, the Institute of Electrical and Electronics Engineers, the Harvard University, the Perdue University, the American Philosophical Society, the Nobel Foundation archives, the Niels Bohr Library and Archives, and other institutions, like in [33-35]. In Russian, the most detailed biographical account of E. Purcell and F. Bloch was given by N. E. Zavoiskaya [26].

Fortune seemed to favor E. M. Purcell throughout his entire life. He was born in a small American town of Taylorville, Illinois, some two hundred miles southeast of Chicago, in a Presbyterian family. His mother, Elizabeth, taught Latin in a high school in Taylorville. His father, also Edward, was manager of the local telephone company. Hence, for his son the discarded electronic equipment and periodic issues of scientific journals, like the Bell System Technical Journal, were part of his everyday life. When in high school, his family had moved to Mattoon, Illinois – a bigger town closer to Chicago, where Edward, together with his equally enthusiastic school friend, took an interest in chemical experiments. His chemistry teacher was a great influence on him – as Purcell himself reminisced, “it was the first time I had encountered any grownup who was a real scientist” [35]. The woman who taught him physics was not that much versed in her subject, but she respected it and fostered that respect in her students. “She introduced me to physics in a humane way that probably was important”, – he said in one of the interviews [35].

As Purcell himself recounted [35], for him, a high school graduate in late 1920s, the name of Steinmetz, a famous electrical engineer, was “more familiar and exciting than the name Einstein”. Edward entered the Perdue University, Indiana, to study electrical engineering. His aptitude for research did not go unnoticed and eventually he studied under the tutelage of Karl Lark-Horovitz (1892-1958, an Austrian immigrant), the man who brought the Perdue University to prominence. In 1933, after he had graduated from Perdue University with the degree of Bachelor of Science in Electrical Engineering, Purcell was awarded an exchange fellowship in Europe, in Germany to be precise, at the time the world’s most important center for physics – namely, he went to Technische Hochschule in Karlsruhe (Karlsruhe Institute of Technology, now part of the University of Karlsruhe). Unfortunately, it was the very time when the Nazi Party was rising to power, a political development to which academic life was not immune either. Professor Walter Weizel (1901-1982), a theoretical physicist whose lectures on physics Purcell attended, for example, was forced to temporarily leave the Institute for his anti-Nazi views. As an exchange student, Purcell spent in Karlsruhe one year, and, despite the disturbing political circumstances, it happened to be a lucky turning point in his life. On his way to Germany Edward met another exchange student, Beth C. Busser. She was going to Munich to study German literature. Although Busser had little to no interest in physics, she accompanied Purcell to the lectures given by the distinguished physicist Arnold Sommerfeld in Munich – she helped take notes. Four years later, not long before Purcell earned his PhD, they got married, for life. Edward and Beth had been together for 60 years and raised two sons.

On his return to the United States, in 1934, Purcell won a scholarship to Harvard and joined the Department of Physics as a graduate student, with the support of Lark-Horovitz. There, at first, he was involved in electron diffraction studies of thin films to later embark on other research projects (including his investigation of magnetic properties of salts at liquid helium temperatures [36]). One of his projects, the study of the focusing properties of charged particles in a spherical condenser, provided him with his dissertation and his Doctor of Philosophy degree in 1938. Purcell was also on the team constructing the first Harvard cyclotron. He helped to build a magnet for it [34].

Throughout the World War II Purcell worked at the Radiation Laboratory established at the Massachusetts Institute of Technology in the autumn of 1940. There he joined a team of American and British physicists entrusted with developing a military microwave radar technology. The Rad Lab was a gigantic institution employing up to 3500 people at its peak in 1945. By the end of the war the innovative designs developed by its scientists resulted in mass radar production. It looks like some of the equipment was supplied to the Soviet Union under the Lend-Lease Act for military purposes. The series of books, commissioned by the Laboratory to preserve the technology developed within its walls and to the writing of which Purcell and his NMR apparatus co-authors contributed, included, according to N. E. Zavoiskaya, 28 volumes! Some of these books were translated into Russian and were in wide circulation among the Soviet laboratories researching ultra-high frequencies and radar technology.

In his Radiation Laboratory years Purcell worked directly with Isidor I. Rabi, associate director of the Laboratory and father of the experimental magnetic resonance method, as well as with some other physicists, who partook in the first magnetic resonance research. With this in mind, it comes as no surprise that after the war was over, since the autumn of 1945 up till 1954, Purcell and his close associates had been directing their major efforts to the development of NMR theory and methods (more on this in “The Part E. K. Zavoisky, E. M. Purcell, and F. Bloch Each Played in the Development of Magnetic Resonance Theory, Methods, and Applications” Section). In those same years he carried out other equally groundbreaking research. The last century can undoubtedly be dubbed as “the Century of Radio Physics”, among its other history-inspired names. Midway through the century were the years when radio instrumentation was taken by its designers to the new level of sensitivity, horizons for its application dramatically broadened. NMR was a new development in radio spectroscopy, but Purcell made a major contribution to yet another field of science – to radio astronomy. Together with Harold Ewen (see Fig. 11), his PhD student, Purcell was the first to detect radio emission

Fig. 11. Horn antenna used by Harold I. Ewen and Edward M. Purcell at Harvard University in 1951. Source: The Free Encyclopedia; URL: https://en.wikipedia.org/wiki/Edward_Mills_Purcell.

from the neutral atomic hydrogen gas in the Milky Way, also referred to as the 21-centimeter radiation, with a horn antenna placed at the top of one of the Harvard's buildings [37].

Average interstellar atomic gas density is less than 1 atom per cm^3. The bulk of gas is contained in a layer of several hundred parsec at a close distance from the galactic plane. The gas density averages around 10 to 21 kg/m^3. The idea of hydrogen atoms presents in the interstellar medium and thus of the possibility of radiation at the frequency of 1420 MHz ($\lambda \approx 21$ cm) had already been discussed by astronomers for several years before the experiment. I. S. Shklovsky, a Soviet astrophysicist, for example, back in 1948, performed detailed calculations for the neutral hydrogen line, predicted by H. C. van de Hulst (the Netherlands) in 1944, and demonstrated, that the intensity of galactic radio-frequency radiation within this line was high enough to be detected with the equipment available at the time.

This radiation is emitted when a transition occurs in an H-atom between the energy levels of antiparallel magnetic moments of a proton and an electron, induced by Fermi interactions of the $F = A\mathbf{IS}$ type, where **I,S** are spin operators of the proton and the electron, respectively. This interaction, originating from the collision between an electron occupying an *s*-orbital and a proton, had been predicted by Enrico Fermi [38] with the use of the Dirac equation, years before the Ewen–Purcell discovery. For its comparatively small magnitude (if compared to both Coulomb interaction and to "fine" spin-orbital interactions) this interaction is called 'hyperfine', and for its nature it is called 'contact'. When no external magnetic field is applied, the energy $2\pi\hbar A$ equals the difference between the triplet state energy (parallel spin pairing) and the singlet state energy (antiparallel spin pairing). Observing radiation from the interstellar clouds of atomic hydrogen makes it possible to estimate their density as well as presence or otherwise of interplanetary dust clouds in the space between them and the Earth, among other things. Later on, Purcell took part in a number of other astrophysical (radio astronomical) research projects [39-41].

Early in 1950s another original work was published, in which Purcell and S. J. Smith discovered emission of visible light by a relativistic electron beam sent close to the surface of a diffraction grating. In some respect, this radiation is comparable to Vavilov–Cherenkov radiation. Interestingly, Purcell, apparently, holds no patent relating to either NMR methods or the Smith–Purcell radiation (as it is now often referred to, as in [42]), while others, with Purcell mentioned and not, took patents on inventions in both those fields. For example, a U.S. patent on the microwave generator using the Smith–Purcell effect was granted to C. A. Ekhdal in 1986 (application filed in 1983), the work by Smith and Purcell [43] referred to in the application. The U.S. patent of F. Bloch and W. W. Hansen on NMR chemical uses, purchased by Varian Associates, is discussed in the last section of this work.

In 1950s Purcell also participated in the research project investigating radio propagation at very high frequencies observable over long distances by means of inhomogeneities in the ionosphere (the team was comprised of eight co-authors from four institutions including the U.S. National Bureau of Standards, the Harvard University, etc. [44]). He also was a part of the team that proved, with high precision, the hypothesis of elementary particles and nuclei having no electric dipole moments (together with Norman Ramsey, Jr. [45]).

In 1949, Purcell became Professor of Physics at Harvard, one of the most respected Departments at the University and in the U.S in general, one may say. He wrote a textbook on electricity and magnetism [46], which was published in 1965 and became Volume II of the Berkley Physics Series (second edition in 1985) (Fig. 12). To the present day this textbook is considered to be one of the most up-to-date physics courses. In the second edition, published in 1985,

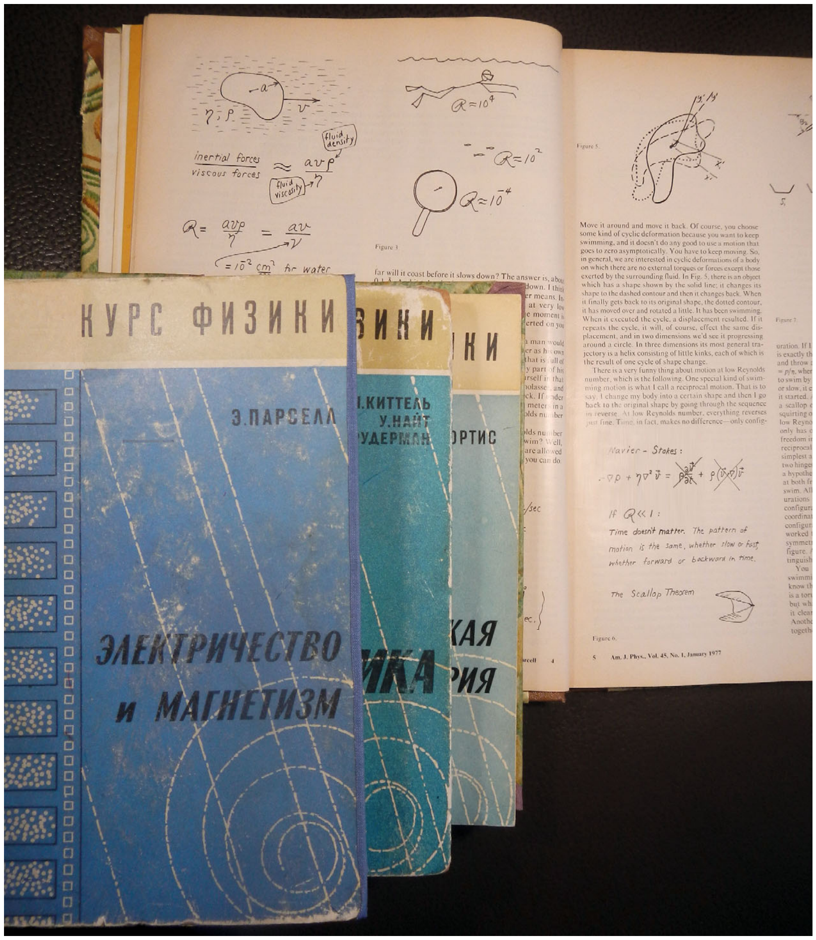

Fig. 12. Collage of volumes of the Soviet edition (1971) of the Berkeley Physics Course, including Vol. 2 (Electricity and Magnetism) by Purcell [46]. A page of the journal with semi-humorous illustration of E. M. Purcell to his paper "Life at Low Reynolds Number" [51] can be seen at the background. Source: V. V. Ptushenko's personal archive.

Purcell, retaining his preferred Gaussian units, included alternative versions of the equations in Système International (SI), thus harmonizing the use of different systems of measurement in the courses of general physics and electrodynamics of continuous media. Purcell's textbook is instrumental in analyzing the differences in using *H* and *B* in the formula notations for magnetic resonance effects (and for other magnetic field phenomena) [47].

In 1962, Purcell joined yet another attempt at finding Dirac monopoles – this time the search was for magnetic monopoles produced in collisions of the 30-BeV protons with different targets at the Brookhaven alternating gradient synchrotron. The result was a negative solution for the collisions of protons with heavy nuclei [48], with an accuracy of 10^{-40} cm^2 cross sections. This problem – set by Dirac with many unknowns, like the said monopole mass and magnetic charge – added a negative experiment outcome to the Purcell's otherwise brilliant track record of solving scientific enigma. As A. Abragam remarked on this episode in his career: "the best hunter comes home with an empty bag if the game is not there".

In 1967, Purcell took an interest in some biophysical problems, namely in those relating to biomechanics: his collaboration with H. C. Berg, a Harvard biophysicist, resulted in the U.S. patent for an elegant particle separator [49] and a number of publications [50]. In 1967 the *American Journal of Physics* reprinted his talk intriguingly titled "Life at Low Reynolds Number" with the figures reproducing the transparencies used by Purcell in the original talk and made by his hand [51] (Fig. 12). The paper described locomotion of *E. coli* bacteria in water. In the same very 1977, with the above-mentioned Howard Berg, Purcell published a joint paper on bacterial chemoreception [52].

In 1970 Purcell became the President of the American Physical Society. Up till 1980 he was teaching at the University, and in 1980s he was a regular pedagogical contributor to the American Journal of Physics, including writing an educational column under the name "Back of the Envelope" ([53] and other issues).

FELIX BLOCH: BIOGRAPHICAL ACCOUNT

Felix Bloch (Oct. 23, 1905-Sep. 10, 1983), a historic figure in the 20th century physics, who shared the 1952 Nobel Prize for Physics with Edward Purcell, was born in Zurich, Switzerland, to a family of Gustav Bloch, a wholesale grain dealer, and Agnes Bloch (née Mayer). A concise but detailed account of his life is available at the Nobel Foundation archive [54] (see Fig. 13). Among the many materials devoted to his life and work and available across the Internet, the interviews he gave in person and his colleagues' memoirs stand out [55-57].

Felix Bloch attended a gymnasium run by the Canton of Zurich, which he graduated in 1924. With mathematics and astronomy taking his particular interest, he (like E. M. Purcell) chose engineering as his future profession and entered the Federal Institute of Technology (Eidgenössische Technische Hochschule) in Zurich. One year into his studies, though, he changed from engineering to physics having made a decision to become a theoretical physicist instead. Between the years of 1924-1927 he studied at the Federal Institute of Technology, Perter Debye and Erwin Schrödinger among his teachers. In 1928, Bloch defended his dissertation and earned his Doctor of Philosophy Degree at the University of Leipzig under the direction of Werner Heisenberg, who suggested that he should dedicate his thesis to the study of conductivity of metals by applying the quantum mechanical theory. Significance of this paper cannot be overstated, for in it Bloch provided the basis for a number of fields in solid state physics by formulating a theorem for the electron wave functions in metals (Bloch function or Bloch waves or Bloch state).

In the years following publication of his doctoral thesis, Bloch held a number of assistantships and fellowships, through which he worked with Heisenberg, Bohr, Fermi, and Pauli. That was the time when he made arguably his biggest contribution to theoretical physics. Bloch gave a theoretical justification for the empirical Grüneisen's rule connecting conductivity of metals to temperature – nowadays it is known as the Bloch–Grüneisen relation. More than several theorems and phenomena bear the name of Felix Bloch following his contribution to the theory of superconductivity and his theoretical treatment of magnetic systems. Among them are: the Bloch's theorem in the theory of superconductivity; the Bloch's $T^{3/2}$ law for temperature dependence of magnetization; the Bloch walls (a transition region between two domains in a ferromagnetic material with antiparallel spontaneous magnetization alignment). In 1932, he developed further the ideas of Niels Bohr and Hans Bethe on the stopping power of charged particles in matter and, as a result, obtained the famous Bethe–Bloch formula. Most of the outstanding papers mentioned here he worked on and published in Germany.

Fig. 13. Felix Bloch. Source: The Free Encyclopedia; URL: https://en.wikipedia.org/wiki/Felix_Bloch.

When, in 1933, Hitler came to power in Germany, Bloch, a Jew by birth, left the country to never return. He spent some time in Europe – Zurich, Paris, Copenhagen, Utrecht, and Rome – giving lectures and continuing his scientific work. Among his options for a secure place to work from then on, he considered the Soviet Union as well. Through his work with W. E. Pauli, Bloch knew L. D. Landau in person and, in 1931, upon Landau's invitation, he visited Leningrad. He was also personally acquainted with another Soviet physicist, Y. G. Dorfman. There are three letters Bloch wrote to Dorfman, all three now kept at the museum of St. Petersburg Polytechnic University, from which it is clear that he considered accepting a position at the nascent Ural Institute of Physics and Technology offered to him by Dorfman (for more on this see N. E. Zavoiskaya's book [26]).

Bloch understood all too well how fragile was the situation in Europe in the face of the rising Nazism, as he understood the dangers of being a foreigner in the Soviet Russia. So, in 1934 he left Europe for the United States, where, as a "displaced German scholar", he was offered a position at Stanford University [56]. In 1939, he became a naturalized citizen of the United States. In 1940, Felix Bloch married Lore C. Misch, another physicist, who had also fled Germany; they had three sons and a daughter.

He joined Stanford as acting associate professor of physics to become full professor two years later. In that period Bloch published a number of important research papers treating problems relating to the quantum theory of electromagnetic field. Then he took an interest in the newly discovered neutron, his research leading him to the assumption that its magnetic moment could be determined by scattering of slow neutrons in the magnetized matter and that the scattering could result in a beam of polarized neutrons. Next year validity of his hypothesis was confirmed. Following his interest in physics of neutron interactions, Bloch turned to the experimental research. In 1930s I. I. Rabi developed his molecular beam resonance method of measuring magnetic moments of nuclei. In 1939, together with Luis W. Alvarez, Bloch experimentally measured magnetic moment of a neutron with the magnetic resonance method similar to the one employed by Rabi. To produce neutron beams they used the 37-inch cyclotron at the University of California, Berkeley [58]. In 1940, together with Arnold Siegert, he published a paper suggesting an approximation procedure for calculating magnetic resonance frequency in the linearly polarized magnetic field [59][10], which proved to be of high significance for the magnetic resonance method.

Unlike E. M. Purcell or E. K. Zavoisky, Bloch thus began his investigations into magnetic resonance in condensed matter armed with some prior experience with magnetic resonance phenomena. During the World War II Bloch was invited to Los Alamos to join the Manhattan Project team, where, for some time, he was researching properties of uranium isotopes. Later, he joined the Radio Research Laboratory, established at Harvard University to develop countermeasures to radar, as an associate group leader in the theoretical division.

When the war was over, shortly after he returned to Stanford University, Bloch embarked upon the studies of atomic nuclei (protons) magnetic resonance, in which radio wave technology, obviously, was employed. For physicists to investigate behavior magnetic moments in atomic nuclei of various types of nuclei they needed to be obtained with high accuracy. To make this possible, Bloch, in 1946, suggested using an original nuclear induction method (for more on this see “The Part E. K. Zavoisky, E. M. Purcell, and F. Bloch Each Played in the Development of Magnetic Resonance Theory, Methods, and Applications” Section). Felix Bloch is renowned for a great many contributions to the advances of physics, but it was the nuclear induction method he was awarded the Nobel Prize for.

After 1946, Bloch devoted most of his time to experimental and theoretical research of NMR (“nuclear induction”) (more on this later). In 1954-1955 he took a two-year sabbatical leave to assume a position of Director General at CERN (the European Organization for Nuclear Research, Geneva, Switzerland), the first in its history. A. Abragam vividly described the CERN period of the Bloch’s life in his book [32]. Suffice it to say, Bloch, according to Abragam, “accepted his position out of good will towards old Europe”, “disliked the “Big Science”[11] and hated administration”.

In the fall of 1955 Bloch resigned his position in CERN and returned to Stanford. In 1971, after his resignation from Stanford, Bloch came back to Zurich, where he passed away on September 10, 1983. Felix Bloch was elected to the American National Academy of Science, American Academy of Arts and Sciences, Royal Netherlands Academy of Arts and Sciences, Swiss Physical Society, and the American Physical Society of which he was President in 1965.

THE PART E. K. ZAVOISKY, E. M. PURCELL, AND F. BLOCH EACH PLAYED IN THE DEVELOPMENT OF MAGNETIC RESONANCE THEORY, METHODS, AND APPLICATIONS

The problem of resonance radiation detected when a transition occurs between the energy levels of magnetic moments differently oriented in the external field was first posed by P. Ehrenfest and A. Einstein [60]. O. Stern’s et al. [61], through experimentation, determined the hydrogen molecule’s proton spin orientation in a magnetic field, a discovery that won him the 1943 Nobel Prize for “his discovery of the magnetic moment of the proton”[12]. Very persistent in his search for nuclear magnetic resonance, although much less lucky, was C. J. Gorter (Fig. 14). In his first attempt [7] to observe the phenomenon with the use of *calorimetric method* for measuring energy absorption, he failed. In the same year, though, Gorter and his team detected absorption and dispersion phenomena in a specimen exhibiting paramagnetism induced by an applied external magnetic field (see, for example, [8]). They thus demonstrated that the energy absorption and dispersion was a function

[10] As is commonly known, the simplest is the equation for a resonance frequency ν_0 in an induced magnetic field B_0, specific (let us suppose, it is clockwise with $\gamma > 0$) circular polarization of the resonance field applied: $2\pi\nu_0 = \gamma B_0$. A linearly polarized field is the sum of two circularly polarized fields rotating in opposite directions. Unfortunately, the Nobel Foundation archive biographical note [54] does not mention this paper [59] which resulted in another phenomenon – changing of the above equation due to effect of the counter-rotating polarized field – taking Bloch’s name (Bloch–Siegert effect or Bloch–Siegert shift).

[11] Accelerators.

[12] Full prize motivation reads as follows: “for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton.”

of electromagnetic oscillations frequency, both impacted by the intensity of magnetic dipole transitions, also (resonance) frequency-dependent. However, for some subjective reason (possibly, he considered electron magnetic resonance lines too broad, or the required range of accessible magnetic fields and frequencies was not available), Gorter never tried to detect electron paramagnetic resonance.

Not long after, I. I. Rabi and his group observed nuclear magnetic resonance with his molecular beam method [4] (Fig. 15). A couple years later, the same group of physicists observed electron paramagnetic resonance in atomic beams [62]. Finally, F. Bloch and L. Alvarez determined magnetic moment of a neutron by means of the cyclotron-produced polarized neutron beam [58]. In all the three experiments resonance absorption was registered by particle detectors, when particles, excited by magnetic resonance, "jumped" from one orientation to another. All this groundbreaking research prompted a string of discoveries in the vast field of magnetic resonance phenomena. Meeting particular conditions, though, was a prerequisite for any specific line of investigation to yield successful results.

In the same period (1940-1941), E. K. Zavoisky, S. A. Altshuler, and B. M. Kozyrev had been performing their own experiments, in which they all but succeeded in observing nuclear magnetic resonance in matter. The Soviet physicists were the first to utilize the radio physical methods to register resonant absorption and dispersion induced by magnetic resonance. With a far more sensitive method at their disposal, they were not discouraged by Gorter's failure, and the advances made by Rabi's group were inspiring. Zavoisky was determined to exploit potential of the "grid current" method in scientific research to the maximum [63]. In the years of 1935-1939 Evgeny Konstantinovich published a series of papers, in all of which he employed this method to study electromagnetic energy absorption in different substances (electrolyte solutions, crystalline acids and salts, etc.). None of the papers, though, demonstrated results of particular interest or practical importance. Zavoisky decided to use the "grid current" method in his magnetic resonance research. First promising results began to take shape. Tragic circumstances triggered by the breakout of the World War II, though, put a stop to his NMR experimentation (for details see [26, 47] and other sources). To continue, he "only" needed to get hold of another magnet or to update the one he had at his disposal. At the very first opportunity – in wartime Kazan it was equivalent to the slightest possible chance – Zavoisky returned to his magnetic resonance research, only this time he studied electron paramagnetic resonance instead. Unlike C. J. Gorter, pedantic but indecisive, Evgeny Konstantinovich started straight away with investigating the media in which EPR was expected to be observed, those with the maximum or near maximum concentration of paramagnetic electrons (third-row transition metal salts and their concentrated solutions).

The reasoning behind his decision to move his focus to EPR instead of NMR is somewhat of a mystery up to the present day. Indeed, Altshuler and Kozyrev both mentioned, more than once, this change of focus in their reminiscences: "In 1943, Evgeny Konstantinovich decided against continuing with NMR research to embark on the studies of paramagnetic relaxation for perpendicular fields instead... Meanwhile, it was absolutely unclear why Evgeny Konstantinovich, who came up with and performed the <...> modulation in 1943, made no attempts at observing NMR. It would have been easier than to observe EPR. There was no need to modify anything, all that needed to be done was to place a vial with water inside a fully functional apparatus. Apparently, Evgeny Konstantinovich was fascinated by his EPR investigations to the point when everything else was neglected", S. A. Altshuler shared with the audience of the First Zavoisky Readings held at the Kazan University on 15 October, 1982 [27]. I. I. Silkin, founder and director of the Museum-Laboratory of E. K. Zavoisky at the Kazan State University, believes there was no "change of focus" *per se*, rather his investigations were not confined to NMR only and he searched for a signal within a wide range of parameters (I. I. Silkin, a personal message). His judgment is supported by the records in the Zavoisky's laboratory notebook for the period of late 1943-early 1944, in which, along with studying paramagnetic losses for paramagnetic species, he frequently mentioned planning to do experimental research "pertaining to the expected nuclear spin resonance", as well as drew tables of resonance wavelength values for different nuclei he calculated, etc. (excerpts from the laboratory notebook were published by Silkin in his book [9]). At the same time, according to S. A. Altshuler [27], "In 1946, Purcell and Bloch published their papers, both announcing they observed NMR. I was there when Evgeny Konstantinovich looked through the papers. He was not disappointed. On the contrary, he was glad the apparatuses were largely the same as his. He considered those papers a continuation and development of his EPR research."

There is a Latin proverb "Fortune favors the bold". Early in 1944, Zavoisky observed EPR in the frequency range between 10 to 100 MHz and higher in the fields produced by means of solenoids with no iron core and providing for magnetic induction ranging from 3 to 30 G (that is $3 \cdot 10^{-4}$ to $3 \cdot 10^{-3}$ T). High concentration of paramagnetic electrons did not result in excessive broadening of the EPR line (an outcome Gorter had

Fig. 14. S. A. Altshuler, C. J. Gorter, C. D. Jeffries, Kazan, USSR, 1969. Source: N. E. Zavoiskaya's personal archive.

Fig. 15. E. Lawrence, E. Fermi, I. Rabi, Los Alamos, US, 1942-1943. Source: The Free Encyclopedia; URL: https://en.wikipedia.org/wiki/Isidor_Isaac_Rabi.

presumably expected), quite the opposite – due to the so-called exchange narrowing, determined later by Van Vleck, it caused the EPR line to slim down in the center, its wings though still broadened. Some simple paramagnetic substances – transition-element salts – turned out to be the easiest to observe EPR in.

The discovery of such a fine physical phenomenon in Kazan, severely understaffed and in desperate need of equipment and financing, baffled scientific minds of the Physical Institute of the USSR Academy of Sciences to the point of skepticism. Any doubts were dispelled though when A. I. Shalnikov reproduced the Zavoisky's experiment at the Institute for Physical Problems and validated the discovery. N. E. Zavoiskaya in her book [26] recounts the events surrounding the breakthrough experimentation in detail. His first paper announcing the discovery of EPR in English Zavoisky published with a delay, but still six months before Purcell and Bloch each published theirs. It may not have had any influence on the trajectory of the American physicists' NMR research[13]. Both Nobel Prize winners-to-be had been ready at the starting line, if an analogy can be drawn between science and high-performance sport with its never-ending competition to be pronounced the first, the best, the strongest. This was not, however, the point. Purcell and Bloch had both been working at the world's best radio research laboratories for some five years immediately before they engaged in their respective NMR investigations. Radio equipment was thus their clear choice for observing the phenomenon of interest. Purcell mentioned that early on in his quest for NMR he heard of the second unsuccessful attempt Gorter and Broer [64] made to detect nuclear resonance – with the use of a radio apparatus (working largely according to the same principle as the apparatus Zavoisky built for his experiment). R. V. Pound, one of Purcell's co-authors in his first fruitful NMR experiment, and W. D. Knight [65] later successfully employed this principle (a marginal oscillator with a sample contained in a cylindrical coil) to quickly detect intense and not too narrow resonances.

Gorter's bad luck with NMR was largely due to his unfortunate choice of substances (diamagnetic crystalline salts) and conditions (low temperatures) for the experiment[14]. But Purcell (a student of J. Van Vleck and I. Rabi) and Bloch (a student of P. Debye, close acquaintance of Van Vleck and an expert in the theory of solids) were not meant to make the same mistake – they both were aware of the nature of spin–"lattice" (molecular oscillations and movement) interaction.

The moral of the story: discovery of magnetic resonance was not a one and done process. The relation between resonance frequency and magnetic induction $\nu_0 = (\gamma/2\pi)B_0$ (the resonance condition; note that in the first papers on NMR, for the resonance condition, H notation was used instead of B, because in the Gaussian unit system then in use, in vacuum, induction as measured in Gauss was equal to magnetic field intensity as measured in Oersted. On top of this, according to H. Kopfermann [66], G. Mie and A. Sommerfeld both used H, not B, as a notation for induction; see also [47]) was, by 1945, known for proton, electron, and several more nuclides (at least approximately). As was well known that, at resonance frequency, magnetic induction of the alternating field must be perpendicular to magnetic induction of the polarization field. What else was there to be discovered? At times, gyromagnetic ratio γ for a particular nuclide NMR was to be determined (measured), that is, in modern terminology, EPR $g = \gamma/2\pi\beta$, in which β is a Bohr magneton, for a particular molecular or nuclear system containing an unpaired electron. At times, signal power or excitation process was to be chosen, according to the spin–lattice interaction conditions. In a word, magnetic resonance, determined by Rabi experimentally, had to be observed again and again in totally different circumstances, or re-discovered all over again for every new object if you will. Interaction between the paramagnetic substances with high electron concentrations and resonance field (EPR for transition element salts) was discovered by Zavoisky. EPR of minor transition element impurities in the diamagnetic crystals, within a wide temperature range, was first studied by the group of B. Bleaney at Oxford [67]. EPR of the stable free radicals was first observed by B. M. Kozyrev and S. G. Salikhov [68], Zavoisky's collaborators. Their research narrowly escaped being stamped classified and thus, unfortunately, it was published later, when similar papers by their colleagues in the West had already been released. In 1949, EPR in the crystals colored by irradiation was observed for the first time [69], etc.

An altogether different story unfolded with respect to observing nuclear resonance – that is, NMR

[13] But it definitely had an influence on and *de facto* facilitated research on EPR resulting in the first papers on the subject to be published a year later.

[14] To observe NMR, the difference in population between the magnetic spin levels must not equalize too quickly by transitions induced by magnetic field at resonance frequency, that is the resonance must not be saturated. To avoid saturation there must be quite intense interaction between the spins and lattice oscillations or molecular movement. Such interaction intensifies, when there are paramagnetic impurities present, temperature somewhat increased.

in diamagnetic substances. The latter included gases, liquids, glasses, crystals, etc., conditions for the spin–lattice or spin–spin interactions different in every case. Analysis of the papers published immediately after NMR was first observed clearly shows that Purcell, much like Zavoisky, was driven by the ambition to maximize the use of radio equipment, its capabilities unprecedented for the time in scientific research. A modest set of radio apparatus Zavoisky had in 1940s paled in comparison to what Purcell, Torrey, and Pound had at their disposal. Design of the apparatus E. M. Purcell, H. C. Torrey, and R. V. Pound [15] chose for their NMR experimentation was similar to that of radar equipment in its radio-frequency part, only it was adjusted for a different frequency range (30 MHz or λ = 10 m). That is, they placed the sample (over 750 g of paraffin) in an inductive part of a resonant cavity loaded by the capacity, instead of simply putting it within a coil.

The subjects of the earliest papers on nuclear magnetic resonance co-authored by Purcell are interesting to pay attention to. First, he detected nuclear magnetic resonance for protons in paraffin [15]. It was followed by the NMR for protons observed in hydrogen gas [70]. Then, he investigated anisotropy of NMR properties for fluorine ^{19}F nuclei in a single crystal of CaF_2 [71]. Three years later a paper on NMR in rigid crystal lattices was published, which introduced the phenomenon of NMR second moments to practical spectroscopy [72]. Finally, nuclear magnetic resonance in solid hydrogen was studied [73].

Numerous times Purcell shifted his focus to the study of NMR phenomenon specific properties and the nature of interactions between the magnetic moment system and an apparatus or a substance (the lattice). Such "digressions" led to publication of a number of papers. Among them are: the paper by Purcell and Pound on the nuclear spin system at negative temperature [74], and the famous BPP paper – the paper by Bloembergen, Purcell, and Pound on relaxation effects in liquids containing hydrogen [75]. The latter for many years had been a classic of practical spectroscopy of liquid solutions for analyzing line broadening and saturation effects pertaining to NMR. The paper on NMR line shapes, by Pake and Purcell [76], had a profound effect on the terminology now in use in NMR spectroscopy. In particular, it set the stage for modern line shape functions classification (in "zero approximation" – Lorentzian and Gaussian line shapes).

Among the Purcell's works, which had an impact on physics in general, his paper on spontaneous emission probabilities at radio frequencies, induced by the interaction between a magnetic moment system and a resonant electrical circuit [77] with a high Q factor stands out. From the Einstein relation, the probability of a spontaneous emission A_ν from an oscillator system at frequency ν is proportional to ν^3 (that is to the number of radiation oscillators per unit volume $8\pi\nu^2/c^3$ multiplied by the energy $h\nu$ of the oscillator). However, in a resonator of volume V and quality factor Q, the first of the factors increases $(3\lambda^3/4\pi)(Q/V)$ times, where λ is the wavelength. Purcell presented this paper at the meeting of the American Physical Society immediately after he had observed NMR for the first time. Spontaneous emission effects, detected when a polaron interacts with a resonant structure in crystals, is now also referred to as the Purcell effect [78].

In 1949, Purcell published an important metrological research paper on determination of the proton magnetic moment in Bohr magnetons [79], to which end he compared the diamagnetic (cyclotron) resonance frequency to that of the proton magnetic resonance in one and the same magnetic field.

Together with Herman Carr, he published an outstanding, methodical work [80], which, in many respects, anticipated the multiple-pulse sequence technique for NMR excitation ("spin choreography" – the term R. Freeman coined for the method in his book [81]).

Pulse sequences designed in a specific way are now widely used in chemistry in multidimensional NMR spectroscopy (e.g., Ernst et al. [82]) and in NMR imaging [83, 84].

From this Carr–Purcell research stemmed the method of measuring molecular diffusion coefficient in liquids by multiple excitation pulses applied to an inhomogeneous polarization field.

It also laid foundation for the development of the DOSY (Diffusion Ordered SpectroscopY) method. With this method, signals in the NMR spectrum are differentiated according to molecular weight by separating large (slowly diffusing) molecules from small molecules. The latter are faster diffusing in the region of the sample with different values for polarization field induction and resonance frequency, and produce quickly decaying signals.

For Felix Bloch, the leader of the Stanford group of NMR explorers (F. Bloch, W. Hanses, and M. Packard), inspiration came, we believe, from two sources. Firstly, it was his prior experience with magnetic resonance [58, 59]. Secondly, according to H. Staub, one of Bloch's co-authors, it was his interest in the magnetic properties of a neutron (for the quotation from H. Staub see [26]). To observe proton magnetic resonance, Bloch and his group used an original apparatus. Its receiver coil was arranged perpendicular to the transmitter coil (Bloch's crossed-coil arrangement – pretty much everything he touched was eventually named after him!). Given the electromagnetic signal transmitted by the excitation coil was "steered" to the receiver coil (by means of semicircular copper "paddles") before the resonance occurred, it could only be precession of the proton magnetic moment in the sample that led the signal off to the receiver to be measured. He gave this phenomenon the name of magnetic induction, thus echoing the paper he co-authored with A. Siegert [59], in which magnetic resonance excited under the action of rotating and linearly polarized fields was considered. Bloch developed a simple but efficient theoretical apparatus [85] that phenomenologically described magnetic resonance for a magnetic moment in a macroscopic sample. The vector differential equation or, respectively, the three linear differential equations for each of the components of a magnetic moment, were immediately termed (obviously!) the Bloch equations.

It took some time for the inventors of the two different NMR excitation methods to realize that both were similar in that the phase balance or energy balance was registered by a specific part of the apparatus, although they did vary in their technical execution. The balance is changed by the nuclear magnetic resonance signal, and the Bloch equations are applicable (more often in liquids, as demonstrated by Bloch's further investigations) or inapplicable (according to the nature of the substance NMR is observed in) independent on the method used to excite or receive the signal. In zero approximation, the Bloch equations describe behavior of the magnetic moment in basically any substance.

Bloch did not hesitate to use his method to perform another series of measurements to determine the magnetic moment of a neutron, including in its free state, with higher precision. Next, by means of the nuclear induction method, the magnetic moment of deuteron was determined [86] with that of tritium (a heavy isotope of hydrogen, its nucleus containing two neutrons and a proton) to follow suit a year later [87].

Finally, on his initiative, Larmor precession frequencies for neutrons and protons were determined in the same magnetic field [88]. Thus, Bloch followed through with his plan he shared in the early months upon his return to Stanford.

Nuclear relaxation in gases resulting from nuclei interaction with paramagnetic centers on the surface of a container filled with gas was studied in a standalone paper [89]. According to Bloch, in gases (as in liquids), paramagnetic centers act as a catalyst in order to obtain sufficiently short relaxation times for the establishment of thermal equilibrium. His last experimental research in the field [90] proved to be instrumental to the development of NMR equipment. In this last experimental paper, Bloch proposed quickly rotating the specimen[15] to eliminate the influence of the magnetic induction azimuthal inhomogeneity on the observable NMR line broadening. This method soon became firmly established in the high-resolution NMR laboratory practice. At the time, it increased resolving power of spectrometers almost ten times.

After 1952, Felix Bloch returned to his theoretical investigations. He concentrated on the treatment of the equations now bearing his name, the Bloch equations, assessing their applicability from the viewpoint of statistical physics [91, 92]. Anatole Abragam, who later integrated the key ideas presented in those works into *The Principles of Nuclear Magnetism* [93] – the Bible as this volume was sometimes referred to [32] – described his reaction in such a way [32]:

"When he asked for my opinion of it, I replied in one word: 'Wagnerian[16]'".

In some of his later papers, Bloch treated problems relating to the quantum statistical theory as pertaining to NMR as well [94, 95].

One of the Bloch's co-discoverers of NMR (William Hansen, who died untimely in 1949) had close ties with the Russell and Sigurd Varian brothers, entrepreneurs highly competent and busy in the field of electronics (Fig. 16). Back in 1946, it was their idea to apply for a patent on the "Method and Means for Chemical Analysis by Nuclear Inductions" According to Weston Anderson, neither Bloch nor Hansen showed any particular interest in pursuing the patent, but Russel was persistent and took it upon himself to file a US patent for them [96]. The patent was granted in 1951 with exclusive rights assigned to Varian Associates, a family business of the said brothers. In its first claim the final text of the patent covers all magnetic resonances, EPR included. The story of this patent Weston Anderson told for the Encyclopedia of Nuclear Magnetic Resonance [96]. In his letter to N. E. Zavoiskaya, dated 2003, R. Pound also mentioned that the text of the claim was later changed to include EPR [26]. The stories told by Anderson and Pound both speak to the fact that the claim was "edited" later to strengthen the company's positions against other market players, contending for similar inventions.

For over 15 years Varian Associates had been the leader in NMR instrumentation development and its investment in the patent, including royalty paid to Bloch and Hansen, certainly paid off generously. Nuclear magnetic resonance, instead of remaining

[15] If the frequency of rotation $\nu_{rot} \gg (\delta B \cdot \gamma)$, where δB is the maximum azimuthal inhomogeneity of the magnetic field induction in the sample, the spectrometer registers a magnetic resonance frequency equal to the mean value (it averages the frequency range and narrows the resonance line).

[16] An allusion to the grandiose style of operas by Richard Wagner.

Fig. 16. Brothers Russel (left) and Sigurd Varian (right). Source: Sempervirens Fund, URL: https://sempervirens.org/news/russell-varian-the-man-who-helped-win-the-battle-of-britain-and-create-castle-rock-state-park/.

a “lonely idea”, as Loren Graham once put it [97], yielded profits and provided for its own further development. (For instance, the patent by W. Anderson and R. Ernst [98] underlying the transition from continuous-wave NMR to pulsed-gradient Fourier transform NMR was based on the inventions made in the laboratory of Varian Associates. Papers published by other researches, though, gave Varian’s competitors grounds for bypassing this patent as well.)

Up until the beginning of the 21st century, Varian was the major player on the market of NMR instrumentation (till the 1980s, EPR instrumentation included), in particular in its chemical analysis segment (visionaries, aren’t they are!). Its closest competitor, Bruker Corporation, originally a Swiss-German company Bruker–Physik AG, was established a decade later, but eventually grabbed the biggest market share. The fact that Bruker–Physik AG and the like were established and succeeded demonstrated that open access research published by Purcell, Zavoisky and other explorers of magnetic resonance phenomena created loopholes for the Varian competitors to get around the Bloch–Hansen patent.

Students of Purcell, outstanding scientists N. Bloembergen, H. Carr, R. Pound, G. Pake, H. Torrey, all made significant contributions of their own to NMR research. Among them, the most impressive strides, albeit in another field, were made by N. Bloembergen (the Nobel Prize 1981 winner for the development of laser spectroscopy). Their papers, with Purcell as co-author, were referred to above. The famous Pake Doublet – a characteristic NMR line shape seen in the crystalline hydrates, which arises from dipolar coupling between the two isolated protons in H_2O – is worth mentioning in this context as well [99].

Many of the Bloch’s collaborators continued their research in the laboratory of Varian Associates. Among them were Martin Packard, the youngest in the group that observed NMR, and a successful researcher and inventor Weston Anderson, who was mentioned earlier in the context of the Bloch–Hansen patent story. The Bloch equations were solved for the case of rapid resonance passage by the theoretical physicists R. K. Wangsness and B. A. Jacobsohn [100]. Later, Wangsness contributed to the quantum-statistical treatment of the Bloch equations [91].

Bloch and Purcell both had direct influence on the development of NMR research in the USSR. The first paper on NMR published in the Soviet Union, by K. V. Vladimirskii, provided references to both their works [101]. A collection of selected research papers on NMR published by ‘Inostrannaya Literatura’ (Foreign Literature Press) in 1942-1950 served as a reference book in the S. D. Gvozdover laboratory in Moscow State University, for example[17].

In 1950-1951, NMR found its application in a number of Soviet Research and Development Centers, like Laboratory #3 (now, the Institute for Theoretical and Experimental Physics of the Kurchatov Institute), Sukhumi Institute of Physics and Technology, and Electrosila Power Engineering Plant in Leningrad (more on this in [102]) immediately following its discovery by Bloch and Purcell.

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Ethics approval and consent to participate
This work does not contain any studies involving human and animal subjects.

Conflict of interest
The authors of this work declare that they have no conflicts of interest.

[17] S. D. Gvozdover’s first paper on NMR [Gvozdover and Magazanik, 1950] was published right in 1950.

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