World War II and its Impact on the Studies of Magnetic Resonance: 1939-1973

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Introduction

Though the Scientific Revolution and the Industrial Revolution had taken place much earlier, it was from the twentieth century that science had had a massive and novel impact on the conduct of warfare. World War I had shown the development of poison gas and Germany's production of synthetic oil, both the products of the technological revolution based on the chemical industry. In the inter-war period the importance of scientific research for technological innovation steadily increased, thereby laying the basis for further military-scientific research and invention.

The World War II was fought from 1939 to 1945 between two rival military alliances, called the Allies and the Axis, involving most of the powerful nations of the world. The prominent members of the Allies were the United Kingdom, the erstwhile Union of Soviet Socialist Republics, and the United States of America. Three principal partners of the Axis alliance were Germany, Japan, and Italy. The war began in Europe in 1939 with the invasion of Poland by Nazi Germany, and ended in 1945 with the victory of the Allies over Germany and Japan. After the outbreak of World War II, Nobel Prizes in Physics were not awarded in 1940, 1941 and 1942. However, Nobel Prizes in Physics awarded in 1943 and 1944 paved the way for phenomenal advancement of the field of magnetic resonance between 1946 and 1973. It is worth mentioning that four radical innovations during World War II were directly stimulated by scientific research for military purposes: radar, sonar, the proximity fuse, and the atom bomb. The decisive role of radar in the Battle of Britain is widely known. But it was also crucial for the Germans in the Eastern Front, for the Red Army failed to destroy the Luftwaffe on the ground before the Wehrmacht's assault on the Kursk salient on 5 July 1942[1]. Once all this research was carried out, however, it could not be confined to the military sphere. Neither the scientists who carried out the researches, nor capitalism with its constant search for markets, could rest content with one off applications restricted to the military field. For us, the main issue is how war stimulated scientific research and turned the curiosity of scientists into one specific direction.

The emphasis of the present article is on the research activities of the American, British and Russian scientists during the World War II in the field of electrical communication who, based on such knowledge and experience, made various discoveries in magnetic resonance, maser and laser in the years immediately following World War II and also during the cold war period. Historically it re-established the belief that military conflict often led to decisive technological advances, which in turn could accelerate development in many areas of science and technology beneficial to mankind.

The Nobel Prize in Physiology or Medicine for 2003 was awarded for discoveries concerning magnetic resonance imaging (MRI), a breakthrough in medical and diagnostic research. MRI is a non-invasive, non-x-ray and non-computer tomography diagnostic technique that uses nuclear magnetic resonance to form cross-sectional images of the human internal organs. Magnetic resonance drew attention of the scientific community immediately after its discovery in 1938. Various forms of magnetic resonance experiments, discovered between 1938 and 1956 included molecular beam magnetic resonance (MBMR), electron paramagnetic resonance (EPR), nuclear magnetic resonance (NMR), ferromagnetic resonance (FMR), and electron nuclear double resonance (ENDOR). Between 1952 and 1960, microwave amplification by stimulated emission of radiation (MASER), an offshoot of magnetic resonance, was developed. Maser was the forerunner of light amplification by stimulated emission of radiation (LASER). The importance of magnetic resonance and its associate branches of science can be judged from the fact that ten Nobel Prizes were awarded to fourteen scientists between 1943 and 2003.

Magnetic field effects on atoms

In 1896, Dutch physicist Pieter Zeeman (1865-1943) discovered that emission spectral line of an atom splits into several components when the atom is subjected to a static magnetic field[2]. The splitting (as explained later) occurs basically due to interaction of the magnetic moment of the atom with the external magnetic field. Elaborate explanation of this effect was given jointly by Zeeman and another Dutch physicist Hendrik Antoon Lorentz (1853 - 1928). The Nobel Prize in Physics 1902 was awarded to Zeeman and Lorentz for their researches into the influence of magnetism upon radiation phenomena.

In 1921, German physicists Otto Stern (1888-1969) and Walther Gerlach (1889-1979) conducted a fundamental experiment on the structure of matter at Frankfurt University[3]. By shooting a beam of silver atoms through an inhomogeneous magnetic field onto a glass plate, they discovered that the beam splits into two distinct beams instead of broadening into a continuous band.

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By the early 1930s, physicists knew that matter is composed of atoms, consisting of positively charged protons and neutral neutrons in the nucleus, around which negatively charged electrons revolve. Electron was discovered by J. J. Thomson in 1897. Ernest Rutherford discovered proton in 1918, and James Chadwick proved the existence of neutron in the nucleus in 1932. It was also known that both protons and electrons have intrinsic spin about an axis. The strength of the magnetic field produced due to motion or spin of electric charges in an atom is called *magnetic moment* or magnetic dipole moment. The *electron magnetic moments* associated with atoms have three origins – electron orbital motion, the spin of electron, and the change in orbital motion caused by an external magnetic field. The *nuclear magnetic moment* is the magnetic moment of an atomic nucleus and arises primarily due to spin of the protons.

The Stern-Gerlach experiment thus showed the quantisation of electron spin into two orientations. This was a major contribution to the development of quantum theory of the atom. With the help of this experiment they could also determine the magnetic moment of the silver atom. In 1933 while working at University of Hamburg, Otto Stern measured the magnetic moment of the proton by using a molecular beam method. Stern was awarded the 1943 Nobel Prize in Physics for his contribution to the development of the molecular beam method for studying the characteristics of molecules and for his discovery of the magnetic moment of the proton.

Discovery of molecular beam magnetic resonance

Isidor Isaac Rabi (1898-1988), a physicist of Columbia University, New York, visited Stern's Laboratory at Frankfurt, Germany, in 1927. Beginning early 1930 he made several improvements to Stern's experimental set up with a view to measuring nuclear magnetic moment. In 1937 he succeeded in developing a resonance method to measure nuclear magnetic moment of atoms[4]. An atom has certain fixed energy levels and transition between these levels can take place by means of emission or absorption of electromagnetic radiation. Transition between closely spaced levels can be induced by means of radio-frequency radiation, and this forms the basis for the resonance method, introduced by Rabi. In his method a beam of atoms is passed through an oscillating field, and if the frequency of that field is right, transition between atomic levels can take place. Rabi was awarded the Nobel Prize for Physics in 1944 for developing a "resonance method for recording the magnetic properties of atomic nuclei". Polykarp Kusch (1911-1993), an associate of Rabi in molecular beam magnetic resonance (MBMR) work, did the first measurement of magnetic moment of electron in 1947 and was awarded one half of the 1955 Nobel Prize in Physics.

Development of microwave radar during World War II

Much before the advent of World War II, radio systems for detection and location of distant targets (later called radar) were developed independently in Italy (1933), Japan (1933), France (1934), Germany (1934), UK (1934), USSR (1934), USA (1934) and the Netherlands (1936). The radar was considered as a means of early warning of air-attack. These radars operated mostly in VHF range, i.e., from 30 MHz to 300 MHz frequency band. Attempts were, however, on to increase the operating frequency or, in other words to use shorter wavelengths, in order to get greater accuracy and better resolution. It was realised by the British radar technologists that ideal wavelength of radar should be 10 cm[5].

Prior to World War II, Prof. Mark Oliphant of Birmingham University, UK, had seen a klystron developed by Stanford University, USA, but its output power was insufficient to be used as a transmitter for microwave radar. In December 1939 he asked two young physicists, John Randall and Henry A.H. Boot of Birmingham University, to develop a microwave generator of higher power output. Within two months they produced a new kind of cavity magnetron, an improvement of the cavity magnetron developed in 1935 by Hans Erich Hollmann in Berlin, and fitted that to an experimental microwave radar in May 1940[6].

A seven-member team of British Technical and Scientific Mission, led by Henry Tizard, who was the Chairman of British Aeronautical Research Committee visited USA in September 1940, to exchange wartime secrets with the Americans, in fields such as radar, nuclear research and jet engines. The British delegation also disclosed all technical details of the cavity magnetron to their American counterpart, which made development of efficient centimeter radar or microwave radar possible.

The Radiation Laboratory was set up at Massachusetts Institute of Technology in Cambridge, USA in October 1940 to develop microwave radar systems. A large number of American physicists working on basic physics research in various Universities were appointed during the war years at the Radiation

Laboratory to conduct research on the development of radar systems. Similarly, many British physicists had to stop their basic research and carry on radar research under the British Admiralty. Immediately after the end of World War II both British and American physicists went back to their respective physics departments and subsequently did significant work in the field of magnetic resonance[7].

The phenomenon of magnetic resonance

The phenomenon of magnetic resonance is exhibited by the spin systems of many atoms and molecules whereby the spin systems absorb energy at specific (resonance) frequencies when subjected to a constant magnetic field and an alternating electromagnetic field. Resonance takes place only when the frequency of electromagnetic field comes in unison with the precessional frequency of the spin system. Magnetic resonance provides an experimental method for determining γ- the ratio of the magnetic dipole moment to the angular momentum of a particle directly from measurement of a frequency and a magnetic field. And once it is known, such measurements give important information about the 'environment' of the spin[8].

Discovery of electron paramagnetic resonance

Electron paramagnetic resonance (EPR) or electron spin resonance (ESR) is a technique of detecting magnetic resonance arising from magnetic moment of unpaired electrons in a paramagnetic substance or in a paramagnetic centre in a diamagnetic substance.

Eugeny E. Zavoisky (1907-1976), an Assistant Professor of Physics at the Kazan State University, USSR discovered electron paramagnetic resonance (EPR) in 1944. In his experiments he used manganese sulphate, copper sulphate and anhydrous chromium chloride. His discovery of EPR was, however, not accepted immediately. He was asked by the Academy to repeat the experiments at the Kapitza Institute of Physical Problems in Moscow. Zavoisky assembled the EPR spectrometer and demonstrated the EPR in hydrous copper chloride. He got his doctoral degree in 1945. Zavoisky's first paper announcing discovery of EPR appeared in Russian in 1945[9]. Due to the international political situation at that time, Zavoisky's outstanding work remained unnoticed in the West. In 1940 Zavoisky started a project to observe proton magnetic resonance. Although he detected such resonance in May 1941, he could not observe it in later attempts, presumably due to failure to obtain homogeneous magnetic field[10]. Between June 1941 and August 1943, he had to discontinue his research work due to war. At the end of 1943, he started work in search of paramagnetic resonance. Although Zavoisky was not benefitted from wartime technical exposure, he had sound knowledge in electrical communication techniques in the radiofrequency range. As a result he could develop the EPR spectrometer for his experimentation[11].

Discovery of ferromagnetic resonance

Ferromagnetic resonance (FMR) is a spectroscopic technique broadly similar to EPR and probes the magnetisation of a ferromagnetic sample resulting from magnetic moments of dipolar-coupled but unpaired electrons.

James H.E. Griffiths (1908–1981) led a team at Clarendon Laboratory during the first half of the war in the development of progressively shorter wavelength klystrons – 10-cm (S-band), 3-cm (X-band), 1.25-cm (K-band), and finally 8-mm (Q-band). During the second half of the war he was Secretary of the Communications Valve Development Committee in London. After the war Griffiths returned to Clarendon Laboratory. He decided to study the permeability of ferromagnetic metals like iron, cobalt and nickel. He used surplus military apparatus for his experimental studies in the microwave region[12]. He discovered ferromagnetic resonance[13] and published his work in Nature in 1945[14].

Discovery of nuclear magnetic resonance

In the winter of 1945, Edward Mills Purcell, Robert V. Pound, and Henry C. Torrey discovered nuclear magnetic resonance (NMR) in condensed matter by nuclear resonance absorption experiments at Harvard University, USA[15]. About five weeks after their discovery, Felix Bloch, William W. Hansen and Martin E. Packard independently discovered NMR by nuclear induction experiments at Stanford University in the West Coast of USA[16]. E. M Purcell (1912-1997) shared the 1952 Nobel Prize in Physics with Felix Bloch (1905-1983) for their independent discovery of NMR, now widely used to study molecular structures and to measure magnetic fields. Both the groups observed that when certain nuclei, having effective nuclear spin, were placed in a magnetic field and a radiofrequency radiation applied, they absorbed energy from the radiofrequency radiation and re-emitted this energy when they returned to their original state.

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Dutch physicist Cornelis Jacobous Gorter (1907-1980) made two unsuccessful attempts to observe nuclear magnetic resonance in condensed matter – one just before the success of Rabi's group in Columbia[17] and the other much before the discovery of NMR by Purcell and Bloch[18].

Purcell graduated from Purdue University in electrical engineering 1933 and thereafter spent one year at Technische Hochschule, Karlsruhe in Germany. He joined Harvard University in 1934 for doctoral work, received PhD in 1938, and served as an instructor in physics till 1940. During World War II, he headed a group at the Radiation Laboratory at MIT which developed advanced microwave radar.

Robert Vivian Pound (1919-2010) began his professional scientific work during World War II as a member of the Radiation Laboratory at MIT. One of his first contributions there was the technique of "broad banding". He became responsible for the design of microwave mixers, and developed several devices based on the Magic-Tee, including mixers and frequency discriminators that made possible the stabilisation of the frequencies of microwave oscillators. In 1945 he arrived at Harvard as a Junior Fellow. In a communication Pound revealed, "Ours was the first to succeed in detecting NMR in condensed matter, as distinct from beams, and it was at least five weeks earlier than that of F. Bloch, W.W. Hansen, and M. Packard. The dates on our 'letters', in successive issues of the Physical Review were December 24, 1945 and January 29, 1946. Our experiment was conceived and carried out in the three months between September and December 15, 1945 as a spare-time activity whilst we were full-time employees at the Radiation Laboratory at MIT. We were all mainly engaged in writing the books that preserved our wartime advances in technology. I was responsible for Volume 16, Microwave Mixers, H.C. Torrey was responsible, with C.A. Whitmer, for Volume 15, Crystal Rectifiers, and E.M. Purcell was responsible, with C.G. Montgomery and R.H. Dicke, for Volume 8, Principles of Microwave Circuits, among others. Bloch and Hansen left their wartime involvements in the spring of 1945 and took up full-time academic teaching and research at Stanford, where they started work on the 'nuclear induction' experiment in that spring"[19].

Felix Bloch (1905-1983) was a Swiss physicist who worked mainly in the US. He was educated at the Federal Institute of Technology, Zurich, Switzerland and did doctoral research under Werner Heisenberg at University of Leipzig, Germany. As a refugee from Nazis he arrived at Stanford University in 1934. He became a naturalised American citizen in 1939. In collaboration with Luis Alvarez he made the first experimental measurement of magnetic moment of the neutron. During World War II, his fundamental physics research works were halted. During 1942-1944 he worked for the Manhattan Project, whose goal was to produce an atomic bomb. He thereafter joined the Radio Research Laboratory at Harvard University and was an associate group leader in counter-radar research. The knowledge of radio technique acquired at Harvard helped him immensely to set up the nuclear magnetic induction experiment at Stanford, immediately after the war[20]. William Webster Hansen (1909-1949) was a professor of physics at Stanford. He started work on the problem of detecting approaching aircraft in 1937. The same year, in collaboration with Russell H. Varian and Sigurd F. Varian he developed the klystron tube, a microwave generator, essential to radar technology. During World War II, he made significant contribution towards development of cavity resonators, radar devices and aircraft landing systems. In 1945 he became Head of Stanford's Microwave laboratory[21]. Martin Packard came to Stanford University's physics department as a PhD student to work with Bloch and Hansen on the yet untested but well conceived idea of nuclear induction. He had previous experience of working on passive microwave devices[22].

Other early EPR experiments

British physicist Brebis Bleaney (1915-2006) was a key figure for outstanding progress of post-World War II physics research at Oxford University. During 1937 – 1939, he conducted research in low temperature physics. With the outbreak of war Bleaney's work was interrupted. He was employed by the Oxford University for the Admiralty, primarily to develop microwave radar technology. His work resulted in the development of tunable reflex klystrons at 3-cm (X-band) and 1.25 cm (K-band). In 1943, J. R. Zacharias, from MIT Radiation Labs of USA, who was a coworker of I.I.Rabi in discovering molecular beam magnetic resonance (MBMR), visited the Oxford Group. He realised that the K-band reflex klystron developed by the British group was more reliable and easier to manufacture than the one developed in USA by the Bell Laboratories. As a follow up action, Bleaney was invited to visit MIT Radiation Lab with the klystron. There he could convince Raytheon of Waltham, MA to manufacture them on a large scale[23].

After the war Bleaney became a lecturer in physics at Oxford in 1945. About the same time the observation of nuclear magnetic resonance (NMR) in solids in the United States suggested that the analogous electron paramagnetic resonance (EPR) could be observed in solids using microwave, and a major step was taken by Bleaney at Clarendon Laboratory. In his words, "James Griffths had discovered ferromagnetic resonance in 1945. This and news from USA about NMR made it obvious to me that EPR was an important technique. I started my pupil/graduate student D.M.S. Bagguley on it in October 1946; this was before we heard of Zavoisky – Russian Journals were not arriving nor were they translated. ....Because I was still busy with ammonia, DMSB worked with Griffiths and discovered the EPR spectrum of copper sulphate[24]. My first publication on EPR was 'Paramagnetic Resonance at Low Temperature in Chrome Alum'. For all this work (EPR) we used klystrons and microwave components from our wartime work, very simple cryostats (for liquid oxygen and hydrogen) made in the laboratory workshops, and rather cheap magnets. Little outside funding was needed – a modest annual grant from British Admiralty (our war-time employers) was continued for a number of post-war years"[25].

Within a few years Bleaney and his group conducted extensive electron paramagnetic resonance studies of a wide range of compounds of the transition groups (3d, 4d and 5d), together with the lanthanide (4f) and actinide (5f) groups. These were explained by M.H.L. Pryce and his associates, A. Abragam, K.W.H. Stevens, R.J. Elliott and others. Pryce worked under the Admiralty in the Signal Establishment during the first part of World War II. Both Abragam and Stevens also served in World War II. Elliott, however, graduated in mathematics in 1949 and published his first work on paramagnetic resonance survey in 1951 jointly with his doctoral guide Stevens[26,27].

In USA, American physicist David Halliday (1916–2010), who was internationally acclaimed since 1960 as a physics textbook writer, discovered electron spin resonance immediately after the end of World War II. He wrote in 1988, "I was born in Manchester, England but moved with my parents to Pittsburgh, Pennsylvania (USA) at age six. I spent most of my life in that city, receiving my BS, MS and PhD degrees from the University of Pittsburgh, the later degree in 1941. I spent the war years at the MIT Radiation Laboratory, on microwave radar problems, an experience that formed an ideal preparation for my later work in electron spin resonance. In 1946, I returned to the University of Pittsburgh as Assistant Professor of Physics and remained there, becoming successively Associate Professor and Professor of Physics. I can tell you that the idea of electron spin resonance occurred to me independently, in consequence of a colloquium talk that I gave, at the University of Pittsburgh, on Purcell's nuclear resonance work. I immediately wrote to my friend Robert Cummerow, who had just missed finishing his PhD programme before the war, and invited him to Pittsburgh to work on this subject as his thesis. This he did, completing his thesis work in 1946-47. I also wrote to the office of Naval Research and obtained a research grant for the work"[28]. Halliday and Cummerow observed electron spin resonance in two salts in 1946[29]. The hardware of Halliday's experiment were of military radar origin, viz., a Navy 3-cm test set (type AN/APW – 3A) along with a klystron oscillator 723 A/B from Bell Labs[30]. Halliday, at the time of their discovery of electron spin resonance in 1946, was unaware of similar work of E.K. Zavoisky at Kazan University done in 1945, as neither Russian journals were available in USA, nor were they translated into English then. In Halliday's words "only when our first results were well in hand did I hear about the work of Zavoisky. Let me make it perfectly clear that the priority of discovery is his, based on his undisputed earlier publication"[28].

Other early NMR experiments

Bernard V. Rollin (1911 - 1969) was a British pioneer who conducted first nuclear magnetic resonance experiment in England, at Clarendon Laboratory of Oxford University. In 1940, Rollin invented the reflex klystron at a wavelength of 10 cm. During the war years Rollin worked on development of cavity magnetron used in Radar. Rollin built the first NMR spectrometer and published his paper titled 'Nuclear Magnetic Resonance and Spin Lattice Equilibrium' in November 1946[31]. British physicist Edward Raymond Andrew (1921-2001) also made extraordinary impact on the field of nuclear magnetic resonance. During the war years, 1942-45, as a Scientific Officer at the Royal Radar Establishment in Malvern, England, he was involved in studying the effect of X-band radar. During 1948-49, as Commonwealth Fund Fellow he worked under Edward M. Purcell at Harvard University, USA[32].

Discovery of oscillatory field method of MBMR

In 1949, American physicist Norman Foster Ramsey (b. 1915) modified the MBMR method of Rabi[4] by introducing two separated oscillatory fields, which increased the accuracy of the older method[33]. His method found application in the hydrogen maser and in atomic clocks. Ramsey was awarded the 1989 Noble Prize in Physics for his invention.

Ramsey was the first graduate student of I.I. Rabi at Columbia. World War II interrupted molecular beam research at Columbia University from 1940 to 1945. He was later involved in establishment of Columbia Radiation Laboratory, which produced 1-cm wavelength radar. Ramsey initially headed a group at MIT Radiation laboratory for development of radar at

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3-cm wavelength and thereafter, worked at Washington as a radar consultant to Secretary of War. In 1943 he went to Los Alamos, New Mexico, to work on the Manhattan Project. At the end of the war he returned to Columbia to join Rabi's group to conduct research in MBMR[34].

Discovery of electron-nuclear double resonance

Electron-nuclear double resonance (ENDOR) is a magnetic resonance spectroscopic technique to determine hyperfine interactions between electron and nuclear spins and thus provides detailed molecular and electronic structure of paramagnetic species. George Feher introduced this technique in 1956 when he observed nuclear magnetic resonance via electron spin resonance line[35], at Bell Laboratories.

Invention of MASER and LASER

Albert Einstein (1879-1955) in 1917 introduced the concept and theory of stimulated emission of radiation[36]. He identified three fundamental types of interactions between matter and light, namely, absorption, spontaneous emission, and stimulated emission. A new concept of amplification and generation of electromagnetic radiation, using stimulated emission of radiation by atomic systems was introduced in 1954 at the Columbia University in New York, USA and at Lebedev Physical Institute in Moscow, USSR. The work of American physicist Charles Hard Townes (b. 1915) and that of Russians Aalekshandr Mikhalovich Prokhorov (1916-2002), and Nikolay Gennadiyevich Basov (1922-2001) led to the invention of the MASER (Microwave Amplification by Stimulated Emission of Rradiation) and the LASER (Light Amplification by Stimulated Emission of Radiation).

Townes received PhD degree in 1939 from California Institute of Technology. He served in Bell Telephone Laboratories from 1939 to 1947. During the war years he was involved in designing radar bombing system. After joining Columbia University as a faculty in 1948, he applied his knowledge of microwave radar techniques to atoms and molecules as a potential new basis for controlling electromagnetic waves. In 1951 Townes conceived the idea of using ammonia molecules to amplify microwave radiation. In collaboration with his two students, G.P. Gordon and H. J. Zeiger, he obtained the first amplification and generation of electromagnetic waves by stimulated emission and coined the term MASER for this device[37].

A.M. Prokhorov had graduated from Leningrad State University and did Post-graduate studies at P. N. Labedev Physical Institute, Moscow. He initially did extensive work in electron paramagnetic resonance. N. G. Basov was a student of Prokhorov at the same institute, where he did major work on molecular oscillators.

During the war, Prokhorov was mobilised in the Red Army. In 1944 he returned to the Laboratory of Oscillation of the P.N. Lebedev Physical Institute and started basic research. Basov served in the Soviet Army during World War II. In 1945 he entered the Moscow Institute of Physical Engineering and studied theoretical and experimental physics. In 1952 Prokhorov and Basov jointly suggested the maser principle of amplifying and emitting coherent microwave radiation[38]. These Russian scientists had no radar experience like Townes, but had become interested in microwave as a means for spectroscopy.

Nicolaas Bloembergen (b. 1920), who had graduated from University of Utrecht, migrated to USA immediately after World War II and subsequently made great contribution in development of maser and laser. In his own words, "I arrived at Harvard University in February 1946, and became the first PhD research student of Professor Edward M. Purcell. He had just discovered, with R.V. Pound and H. C. Torrey, the phenomenon of nuclear magnetic resonance. My thesis "Nuclear Magnetic Relaxation" was submitted to the University of Leiden, since I had passed all my examinations in the Netherlands. The years 1946-1947 at Harvard were of course very exciting. I had regular discussions with Professors E.M. Purcell, J. H. van Vleck, R.V. Pound and Professor C.J. Gorter of Leiden, who was a visiting lecturer at Harvard in the summer of 1947"[39]. Bloembergen initially worked in the field of NMR. His joint publication with Purcell and Pound on basic theory of nuclear magnetic relaxation[40] is one of the most quoted papers in physics. The concept of negative absolute temperature introduced by their experiments found later application in the development of maser[41]. In 1956, Bloembergen produced a three-level solid-state maser, which introduced the pumping scheme later utilized in lasers[42].

In early fifties, inventors of microwave maser took major initiative to produce maser at shorter wavelengths. Charles Townes and Arthur Leonard Schawlow (1921-1999) of Stanford University had theoretically predicted in 1958 that maser could be made to operate in the optical and infrared region[43]. During the war years Schawlow taught classes to armed service personnel at University of Toronto, Canada and also worked on microwave antenna development at a radar factory. In 1958 Prokhorov and Basov et al also gave proposals for construction of laser[44,45]. Theodore Harold Maiman (1927-2007) an American physicist constructed the first practical laser unit in 1960 at Hughes Research Laboratories in Malibu, California[46].

The 1964 Nobel Prize in Physics was awarded to C.H. Townes, N. G. Basov and A. M. Prokhorov for fundamental work in the field of quantum electronics, which led to the construction of oscillators and amplifiers based on the maser-laser principle. N. Bloembergen and A. L. Schawlow were awarded 1981 Nobel Prize in Physics for their contribution to the development of laser spectroscopy.

Development of advanced NMR techniques

During early 1950s E. M. Purcell had predicted that NMR would be a tool for chemical analysis. However, for that to happen, it was necessary to increase sensitivity of the early NMR techniques. A major breakthrough in the field of NMR occurred when Swiss chemist Richard Robert Ernst (b. 1933) together with American chemist Weston A. Anderson developed a new method of high-resolution NMR[47] which increased the sensitivity of NMR spectroscopy many folds and made it possible to study small amounts of material as well as chemically interesting isotopes of low natural occurrence. For this contribution Ernst was awarded 1991 Nobel Prize in Chemistry. He also made contribution in high-resolution NMR, which paved the way for advent of two-dimensional NMR technique for macromolecular studies. Ernst and his colleague Kurt Wuthrich (b. 1938) at ETH Zurich, Switzerland, made first experiment of 2D NMR in 1977[48]. Wuthrich, through a number of experiments between 1977 and 1980, developed methods for identification and structure analyses of biological macromolecules. He was awarded the 2002 Nobel Prize in Chemistry. Both Ernst and Wuthrich had sufficient knowledge of instrumentation of NMR spectrometers. Ernst had himself constructed high-sensitivity radiofrequency pre-amplifiers and high-sensitivity probe assemblies for 25-MHz and 75-MHz proton resonance spectrometers at ETH Zurich, while Wuthrich working in Bell Telephone Laboratories in Murray Hill, New Jersey in 1967-68 was responsible for maintenance of the first superconducting high resolution NMR spectrometer operated at 220 MHz.

Discovery of magnetic resonance imaging

The technique of magnetic resonance imaging (MRI) for imaging human internal organs was discovered by American Chemist Paul C Lauterbur (b. 1929) at the State University of New York in Stony Brook, and British physicist Peter Mansfield (b. 1993) at the University of Nottingham. MRI is an exact and non-invasive method which marked a breakthrough in medical imaging and is perhaps the best example of application of a magnetic resonance phenomenon for human welfare[49,50]. Lauterbur and Mansfield were awarded the Nobel Prize in Physiology or Medicine in 2003.

Conclusions

World War II had great impact on the phenomenal advancement of magnetic resonance studies during the period from 1939 to 1973. The major factors which facilitated such advancement were alliance between USA and England for scientific and technical cooperation, large-scale involvement of physicists in these two countries for development of radar equipment, migration of physicists from Europe to USA and military funding for scientific and technical research during the war years.

Decision of the British and American Governments to conduct extensive research on microwave radar was the key factor for development of apparatus and techniques which were used extensively by the pioneers of magnetic resonance research after the World War II. Military funding for scientific research in USA and England during the war years and also during the cold war period gave a boost to this endeavour. Even during the period of cold war, the link between military institutions and fundamental research laboratories in physics, particularly in USA continued to expand[51]. Top grade physicists in USA and England who spent their war years in developing radar and wireless communication techniques and devices returned to basic research immediately at the end of the war.

Nazis rose to power in 1933 and as a result many physicists from Germany had to leave the country. Further, after devastation of Europe during World War II, many outstanding physicists were forced to migrate to USA. Here, within the purview of the present article, we consider the movement of three such pioneers, who subsequently earned Nobel Prizes for USA. Otto Stern, the Director of Physical Chemistry Laboratory at University of Hamburg, left Germany in 1933 and became a research professor of physics at the Carnegie Institute of Technology, Pittsburg, USA, where he worked up to 1945. Felix Bloch, originally from Switzerland, received his PhD degree from University of Leipzig in Germany. He continued research there, but when Hitler came to power Bloch left Germany in the spring of 1933. A year later he joined in Stanford University, Palo Alto, California as a faculty. He returned to Zurich, his birthplace, after retirement from Stanford in 1961. The Germans occupied Holland in 1940, while

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Nicolass Bloembergen was a student at Utrecht University. He received a Phil.Drs degree (equivalent to MSc degree) from the University 1943. Nazis, however, closed the University the same year and Bloembergen emigrated to USA to join University of Harvard in 1945. He became a US citizen in 1958.

Starting from the path-breaking experiment of Stern and Garlach, which was the forerunner of magnetic resonance spectroscopy, seven Nobel Prizes in Physics, two in Chemistry and one in Physiology or Medicine were awarded within a span of 60 years in the field of magnetic resonance and allied branches of science. Out of fourteen recipients of these Nobel Prizes, there were ten Americans, two Russians, two Swiss and one British researcher. Further, from bibliographical survey[52] it transpired that developments of EPR and NMR during 1945-46 immediately drew attention of many physicist and chemists in various parts of the world, namely, in USA, USSR, England, France, Netherlands, Germany, Italy, Canada, Japan, Scotland, Switzerland, and India. During the following decade about seven hundred research papers on magnetic resonance were contributed by fifty laboratories, most of which were located in the USA.

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