PAUL LANGEVIN (1872-1946): THE FATHER OF ULTRASONICS

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***Abstract*— The year 2022 marks the 150th anniversary of the birth of the French physicist Paul Langevin. In February 1917, Langevin invented the first piezoelectric ultrasound transducer, to be used as a means for detecting U-boats using ultrasonic echoes. This discovery opened the way for new scientific and practical investigations, eventually leading to the widespread use of ultrasound for medical imaging. Langevin is widely honoured in his native country, but there is a paucity of biographical material in English. In this article we present a translation of the obituary of Langevin by Frédéric Joliot-Curie, first published by the Royal Society of London in 1951. This translation allows a wider understanding of the life of this outstanding man of science and man of the people, whose fundamental contributions to ultrasonics have remained inadequately recognized.**

Keywords— **Ultrasound, Langevin, Joliot-Curie, Obituary, Medical.**

I. Introduction

The medical applications of ultrasound, diagnostic, therapeutic and surgical, are the most visible and tangible present-day evidence of the scientific work of the renowned French physicist, Paul Langevin. 2022 marks the 150th anniversary of his birth in Paris on 24 January 1872. In this article we present the first English translation of the obituary of Langevin by Frédéric Joliot-Curie, published in French by the Royal Society of London in 1951, five years after his death on 19 December 1946 [1]. Several biographies were published of Langevin in French during the years following his death [2,3,4]. His collected work has been republished [5,6]. There has even been a biography written in Russian [7]. But, apart from occasional more recent brief articles [8], there is a severe deficiency of publications in English about Langevin's extraordinary life and achievements. The following translation will begin to fill this gap.

The biography was signed 'F Joliot'. This French physicist is better known as Frédéric Joliot-Curie (1900-1958), who, with his wife, Marie Curie's daughter Irène, shared the 1935 Nobel Prize for chemistry for their discovery of artificial radioactivity. He had studied under Langevin at the *École supérieure de physique et chimie* in Paris before becoming Marie Curie's assistant. He led the celebration for Langevin's post-war return to Paris in 1945 [9].

Paul Langevin was a Foreign Member of the Royal Society. He received the Hughes Medal in 1915 for 'his important contributions to, and pre-eminent position in, electrical science' and the 1940 Copley Medal for 'his pioneer work on the electron theory of magnetism, his fundamental contributions to discharge of electricity in gases, and his important work in many branches of theoretical physics'. Neither citation mentions ultrasonics nor piezoelectricity. Recognition for his work in ultrasound did not develop until after his death, and remains muted even today.

Joliot's biography sets Langevin's work on ultrasound in the context of his life and other scientific work. In this context, the entry is brief: half a page, set between a summary of Langevin's contributions to the theory of relativity and an overview of his last work in which he developed a theory for the stopping power of fast neutrons, necessary for the design of nuclear reactors. Given the brevity of this entry, it is appropriate to add some more details of Langevin's work on ultrasonics and the piezo-electric properties of natural quartz crystals.

II. Langevin"s discovery

Langevin identified February 1917 as the date when he realised that the piezoelectric properties of quartz might be successfully exploited initially to receive and then to transmit ultrasound. He had already been working with the French Navy for two years to devise an ultrasonic system for the detection of enemy submarines. A Russian émigré, Constantin Chilowski, had pointed out that a practical directional beam of sound could be created if the frequency was high enough, a suggestion that had also been made by the British physicist Lewis Fry Richardson. By the end of 1916 the French team had designed a source of ultrasound at 100 kHz using a 'singing condenser', detecting the waves produced with a carbon granule microphone connected to a wireless receiver.

Langevin had been taught by Pierre Curie in his youth and, as he matured, he became part of an intimate quartet of Parisian physicists, with Marie and Pierre Curie and Jean Perrin. The Curie brothers, Jacques and Pierre, had demonstrated the piezoelectric properties of quartz in 1880 and had devised an instrument, the *quartz piézo-électrique*, with which Pierre and Marie had measured the radioactivity of radium. Langevin realised that this *quartz piézo-électrique* was cut along the wrong plane through the crystal to be efficient to detect ultrasound. A different slice orientation was required, so-called X-cut quartz, for which the electrical and strain axes were aligned. Still, it was not until he tested a single crystal as a replacement for his carbon receiver that he knew that the piezoelectric properties, previously investigated only under static conditions, were retained at 100 kHz. Langevin delighted in this elegantly simple solution, an acoustic aerial that he described as 'a piece of stone, two plates of tinfoil' [10].

A further breakthrough was made later in 1917 by his discovery that the reciprocal nature of piezoelectricity could be exploited to generate ultrasound also. This opened the way to the design of the first pulse-echo transducer, which could be used both to emit a pulse of ultrasound, and to receive echoes. Langevin's discovery was disseminated as widely as possible, given the wartime conditions, to the Allied laboratories in Britain, USA and Italy. By the end of the war, successful ultrasonic pulse-echo systems were being tested by both French and British navies.

Joliot-Curie's obituary includes a pertinent comment about what happened next: "A new chapter in acoustics was opened and experiments .... were made possible at frequencies of several hundred millions per second. Many discoveries in physics and many applications in chemistry and biology have thus been made possible." Indeed, all post-war work on ultrasound derived directly or indirectly from Langevin's breakthrough. The Canadian Robert Boyle, who had led the British asdics team, and was now back in Alberta, investigated acoustic cavitation and ultrasonic metrology. The American Robert Wood had visited Langevin during the war and subsequently set up an ultrasound laboratory with Loomis at Tuxedo Park, New York demonstrating dramatic physical and biological effects. Similar work was carried out by Frank Lloyd Hopwood, physicist at St Bartholomew's Hospital Medical School, London, who had learned of Langevin's work through Boyle. Alexander Nicolson's development of the piezoelectric crystal Rochelle salt followed from the open communication with industrial engineers in the USA, as did Walter Cady's work on frequency control. Léon Brillouin predicted light scattering by ultrasonic waves. More details of these developments have been published in Medical Physics International [11] and elsewhere [12].

During the immediate post-war years, Langevin devoted much attention to the interpretation of Einstein's special theory of relativity [13], but maintained his consultancy with Toulon where he negotiated to establish a transducer laboratory [14]. 1923 marks the year when his wartime work on ultrasonics became public knowledge. In this year he presented an extensive course on ultrasonics at the *Collége de France*, the first of its kind anywhere in the world. He had a reputation as an outstanding teacher. His course included beam formation, acoustic shock formation, transducer design, transmission through layers and the physics of acoustic absorption. The contents were later written up and published by his student Pierre Biquard [15]. This led to further improvements in transducer design and in ultrasonic metrology [16] and supported the successful exploitation for civil echo-sounding and underwater navigation aids by Charles-Louis Florisson. Langevin's work with quartz transducers created the impetus for the development of other ultrasonic transducers for underwater applications using magnetostrictive devices and other piezoelectric materials. In spite of this, quartz remained the transducer material of choice in ultrasound laboratories for several decades.

III The link to medical ultrasound

There is an irony that ultrasound was being used for medical therapy in Germany by 1940, at the same time that Langevin himself was arrested by the Gestapo and subsequently held under house arrest in Troyes. Langevin did not live long enough to know about the first Congress on Ultrasound in Medicine, held in Erlangen in 1949, a congress almost entirely devoted to therapy [17]. His colleague Florisson, who attended the congress, reported that Langevin had predicted the potential therapeutic use of ultrasound. Indeed, there is evidence from a 1925 patent filed by Léon Brillouin that these friends had thought about the therapeutic rather than the destructive effects emphasised by others at this time [18]. However, it was left to the German physicist Reimar Pohlmann to establish its scientific rationale in 1939. By 1950 there were about a dozen manufacturers of therapeutic ultrasound equipment, and all but one of them were using quartz piezoelectric transducers, based on Langevin's discovery over thirty years earlier.

Joliot's biography was written as ultrasound was emerging as a therapeutic agent, but before pulse-echo detection had been investigated for medical diagnosis. By 1972, on the centenary of Langevin's birth, his student Pierre Biquard could finally add medical applications to 'the field of theoretical and experimental research and industrial applications' as outcomes directly attributable to Langevin's work on ultrasonics [19].

There are close similarities between X-rays and ultrasound in their historical passage from discovery to medical use. This is in spite of the obvious difference between the dramatic immediacy with which Roentgen's announcement was taken up by doctors and the long delay and slow subsequent development of ultrasound. Both men, Langevin and Roentgen, were eminent European physicists. Both immediately informed others of their discovery. In both cases, the breakthrough was based on earlier pure science: the investigation of the passage of an electric current through rarefied gasses resulted in the discovery of X-rays and the exploration of piezoelectricity led to practical ultrasound transducers. Both are examples of the enabling technology that led to subsequent developments. For both, the claim to originality was challenged, through Rutherford and Nicholson for piezoelectric transduction and by Lenard for x-rays. In both cases each technology went through an important change: from the gas tube to the Coolidge tube for x-rays: from quartz piezoelectric transducers to ferroelectric ceramic transducers for ultrasound. Both new radiations stimulated fundamental new science, and were exploited in numerous scientific and industrial applications. In medicine, both radiations became used for both diagnosis and therapy. These discoveries form the rootstock of modern medical imaging. Paul Langevin should take his place alongside Wilhelm Roentgen as one of its founders.

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PAUL LANGEVIN 1872-1946

Obituary Notices of Fellows of the Royal Society, 1951;7:405–419

F Joliot

(Translated from the French)

Paul Langevin was born in Paris, in the Montmartre district, on January 23, 1872. His family was of very modest circumstances. His father, after having served as a Zouave in the Army[1], became a building surveyor. He family was from Falaise in Normandy. This small town in Calvados was also home to an Abbot Langevin.

Paul Langevin's mother, Marie-Adelaïde Pinel, was the grand-niece of a psychiatrist [2], very well known at the time and who had been a member of the Academy of Sciences in Paris.

He was attracted to scientific studies early in life and entered the Municipal School of Industrial Physics and Chemistry of the city of Paris where he became first of his class. This school had been very recently created - Paul Langevin was part of the seventh cohort - and it tried to inaugurate, in France, the teaching of physics and chemistry in which experimentation would hold a large part. In this School, which he was later to direct and where he made a profound impact, he was taught in particular by Pierre Curie. He was first in his class, and then moved to the *École normale supérieure,* which he attended between 1894 and 1897. And there, and also in the Physical Sciences *Agrégation* examination[3], he largely out-performed all his classmates, already affirming his exceptional qualities.

When we explore the unfolding of a life, however long and fruitful it may have been, we are almost always led to discover the occasion or the event that was decisive. For Paul Langevin, the granting of a scholarship abroad, in 1897, by the City of Paris, certainly had this character, for the young and already brilliant physicist was thus led to continue his studies at the Cavendish Laboratory in Cambridge. There he made the acquaintance of eminent physicists, who have since become famous, and he retained all his life a vivid memory from this period of his existence. His British colleagues had an impression that was summed up very well by Rutherford when he said to those of Langevin's pupils coming to Cavendish Laboratory – "Tell your Master that he will always be at home here".

1. [1] Possibly a conscript – Zoave were previously an élite infantry corps from N Africa
2. [2] Aliéniste
3. [3] The *Agrégation* is the highest level of French degree assessing suitability to teach a particular discipline at all levels, including higher education.

Back in France in 1900, Paul Langevin continued his research at the Sorbonne, where he was laboratory assistant and then *Chef de Travaux* [4] for the Chair of Physics. This work, initiated at the *École normale supérieure* and continued at Cambridge, focused on the properties of X-rays, discovered shortly before by Roentgen, and on the ionization of gases. On April 28, 1900, his first publication appeared in the *Bulletin de la Société Française de Physique* entitled 'On the ionization of gases'. It is also on this subject that in 1902 he defended his doctoral thesis. So, under the title 'Researches on ionized gases' he published the first overall, experimental and theoretical account of his research on gaseous ions.

In 1905 he succeeded Pierre Curie as professor at the *École de physique et de chimie*. In 1909 he became Director of Studies of this School, where he was overall Director from 1925 until his death. This was an important part of the work to which he devoted all his life, only interrupted by the period during which France suffered from the joint domination of the Nazis and their French accomplices. The latter removed Langevin from his post, while their masters put him under arrest and then under house arrest in Troyes.

But it was not only at the School of Physics and Chemistry that he taught physics with extraordinary mastery. In 1909 the assembly of the *Collège de France*, anxious to maintain at a very high level the teaching and the scientific effort of the establishment, asked Paul Langevin to succeed Mascart. Paul Langevin had already assisted Mascart at the *Collège de France* for seven years. The exceptional value of his work and the fruitfulness of his teaching naturally led the assembly to choose the young and already famous physicist.

Paul Langevin had the pleasure of becoming the close colleague of Marcel Brillouin, of whom he had been a student at the *École normale* first, then at the *Collège de France*. He liked to talk about his former master and to express to him on many occasions his gratitude and affection.

Brillouin was always proud of his pupil and, in 1945, now retired to a small town in France, he wrote him a very moving letter for his 73rd birthday, some passages of which I reproduce below.

‘I often think, in my almost rural loneliness, of the years when I had the pleasure of examining you, for entry to the *École normale*, without being able to find a limit to the scope, the precision, or the clarity of the knowledge acquired by you at the School of Physics and Chemistry which you now direct, and of the conversations with Pierre Curie. When you went to the *École normale*, your mind had already matured, and I do not think I taught you much.

'What added most to your knowledge is the visit that you made to the University of Cambridge shortly after leaving the *École normale*. There you found masters whose teaching was quite different from that given to us in France in primary or secondary education. A mature mind like yours was required to make fairly significant changes in order to make good use of meeting eminent scholars like J. J. Thomson and Lamor, and laboratory colleagues who would soon become famous, like Rutherford, Wilson and Townsend.

Returning from Cambridge you were, in my opinion, the typical professor destined for the *Collège de France* and I had no difficulty in sharing this opinion with my father-in-law Mascart. In this chair, you were able to give the full extent of your ability to assimilate, to complete and to present with astonishing clarity the newest and unforeseen events, caused by the unexpected results of Michelson, the importance of the change of the Lorentz factor and, in its simplest form at first and most complete a few years later, of Einstein's theory of relativity. Others may have written books more quickly on these fine theories; it is from you, at the *Collège de France*, that all those who understand them well, and with clarity, have learned them either from your lessons, or in the meetings with frequent discussions each Tuesday and Friday in the large and uncomfortable physics lecture theatre.

'What didn't you add ?! What have you not sown, then, almost without knowing it, with the remarks suggested to you by the objections and, not least, the comments of some of the assistants?’

Paul Langevin was a member of a large number of Academies and Scientific Societies in many countries. In particular, he had the very high honour in 1928 to succeed H. A. Lorentz, as chairman of the Scientific Committee of the Solvay International Physics Institute. In this capacity he assumed the presidency of the Solvay Physics Councils of 1930 and 1933. He was subsequently a member of the 'Royal Society' and, since June 25, 1934, of the Academy of Sciences of the *Institut de France*. By his scientific work and his teaching of extraordinary fertility, Paul Langevin has greatly contributed to placing physics in a dominant place in the sciences. In experimental work, mark of his thought can be found in the great movement of research and ideas which has taken place since the end of the last century and which has led us to give a more exact understanding of Nature and a better representation of the phenomena which occur there. Experimental discoveries forced him, along with the great physicists of his time, to criticize and profoundly modify these notions, concerning fundamental notions of time, space, mechanics and the structure of matter and radiation.

History demonstrates how turbulent this period was, both from the point of view of science and that of social life. In this turmoil, of which these two aspects are only apparently independent, there are men who have known how to dominate events and hold high the torch of truth. Paul Langevin was one of them.

When he tried to place his work as a physicist in the evolution of Science he liked to say that he had successively lived through the great revolutionary calls of relativity and quanta that physics has experienced during

4.[4] *préparateur* and *chef de travaux* were scientific staff posts the previous fifty years. In this regard, he evoked the difficulties of adapting the mind to new ways of questioning nature. But he was able to overcome these difficulties. In the theory of ions, in the study of dia- and paramagnetism, in the theory of electric and magnetic birefringence, his work is absolutely fundamental. The great movements of ideas created by relativity, quanta and wave mechanics find in Langevin not only a follower, not only a prestigious educator but also a major participant, and he established the famous law of equivalence between matter and energy independently of Einstein.

Paul Langevin has always been convinced of the need for a close and continuous link between pure science and technique, between the scientist and the practitioner so that the latter is informed as widely as possible, through the general culture, through the results obtained by the scientist and where reciprocally the scientist can know the problems posed in practice, with the filtration and the generalization necessary to the various stages of scientific organization, and also to profit from the increasingly powerful material means available to it. He provided a significant illustration of this by resolving in 1915 the problem of the production and detection of ultrasonic waves, thus placing in the hands of the Allies a weapon that proved, during the two wars, so effective in the fight against German submarines.

An exceptionally talented teacher, he taught generations of scientists at the *Collège de France*, the *École de physique et chimie* and the *École normale supérieure de jeunes filles*, by always presenting to them the living aspect of science, of the science that is created. He did not think it necessary to limit his pro-religious activity to these tasks. His universal mind and his precision of judgment enabled him to analyze social problems in depth. Paul Langevin did not want to be part of an elite of scholars detached from real life. It was through action, as a militant in the larger community of workers, that he concerned himself with social problems.

To have fought for peace, for international solidarity, for social justice, against racist theories, all this pointed to Langevin as a target of choice for the Nazis. Despite the risk, Paul Langevin returned to Paris in 1940 and in October of that same year he was arrested, thrown in prison, and then put under house arrest in Troyes. His daughter Hélène was deported and his son-in-law, physicist Jacques Solomon, a fervent Communist, was shot. All these misfortunes deeply wounded Paul Langevin without shaking for a single minute either his courage or his certainty of the final triumph of justice over barbarism.

As Louis de Broglie so rightly said at the *Académie des sciences de l'institut de France*, on December 15, 1947:

'He brought to his opinions such sincerity, such conviction, such a passionate love for justice and suffering humanity that his attitude inspired respect, even in those who did not share his views. He knew how to rise above all petty considerations to that height of thought where all men of goodwill can agree. '

After his exile in Switzerland, Paul Langevin returned to Paris after its liberation and took over the management of the *École de physique et chimie* and his chair at the *Collège de France*. At the same time he was responsible for chairing the commission that was to finalize a profound reform of education in France. His health was greatly shaken by the terrible moral and physical injuries that were inflicted on him by the treasonable government of Vichy and the Nazis. After an existence entirely devoted to the two causes which he considered inseparable, Science and Justice, after having worked much, struggled much, suffered much, after having found and experienced great joys, Paul Langevin died on December 19, 1946. His last words were again to give to those around him confidence in science and hope for an approaching era of justice and kindness.

THE SCIENTIFIC WORK OF PAUL LANGEVIN

Gaseous ions

Langevin's first researches were devoted to the problem of the movement of gaseous ions affected by an electric field. From the experimental form of the saturation curve he deduced the value of the recombination coefficient from the mobilities. The study of the recombination coefficient led him to demonstrate that under the very low pressures prevailing in the upper atmosphere, there exists equilibrium a high concentration of ions in equilibrium. The Heaviside layer is thus explained as well as the persistence of conductivity during the night, when the ionizing action of solar radiation has disappeared. The same cycle of studies lead him to discover in the atmosphere the existence of large ions, whose mobility is several million times smaller than that of ordinary ions and which are made up of water droplets, one hundredth of a micron in diameter, having captured the charge of an ordinary ion. He was also able to give a theory for the formation of two types of clouds: stratus, cumulus or nimbus at an altitude of less than two thousand meters and higher clouds, the cirrus clouds, at an altitude of around ten thousand meters.

Paul Langevin then returned to the theory of free paths in order to generalize and extend it, taking into account the law of probability according to which the paths are distributed between two collisions. He thus dealt in a general way with the problem of mobility and diffusion and established that the ions in gases are constituted by a single layer of molecules maintained by electrostatic attraction around a charged centre. In a study published jointly with J. J. Rey, he demonstrated that the explanation of the conductivity of gases by collisions from thermal agitation was not in accordance with experiment. We now know that cosmic radiation is the origin of this conductibility.

Brownian motion

P. Langevin provided a new justification for Einstein's formula by breaking down the action of a molecular collision on a particle into two terms: one of the terms concerns the normal action and corresponds to the viscosity, the other term is irregular and gives rise to Brownian motion. These kinds of question led him, in collaboration with Jean Perrin, to deepen the meaning of the second principle of thermodynamics so as to underline its statistical character, and to allow for the possibility of limitation (variability).

Electromagnetism

Besides studies on the mass of the electron and the variation of it with speed, Paul Langevin showed that the traditional theory of electromagnetic radiation completely interprets the phenomena of diffusion of light by through fluids, for example. A justification of the blue sky theory can be made in this way if a representation of molecules having an electric anisotropy is introduced. The various physicists who have studied these questions have made systematic use of this model, often referred to as the 'Langevin molecule'. Rayleigh's theory was thus integrated into electromagnetic theory.

Dia and paramagnetism

Paul Langevin made great progress in the theory of magnetism. His first publication on this subject dates from 1905. Paul Langevin took up Ampère's idea of the existence of molecular currents on a microscopic scale in connection with magnetic phenomena, but by introducing the recently-discovered electron. He thus succeeded in developing a theory of diamagnetism and paramagnetism.

Paul Langevin assumed that electrons follow closed orbits inside atoms. If e is the elementary charge, S the area of the swept orbit in time, T the magnetic moment, then M will be $M=eS/T$. The interpretation of diamagnetic phenomena results from assuming that, in such substances, the geometric sum of the magnetic moments is zero. If the whole is subjected to the action of an external magnetic field, the various electrons have their trajectories modified, the new movement being that which originally existed but *vis-à-vis* a system of axes revolving around the direction of magnetic field H, with the Larmor angular velocity $\omega = He/2m$. It follows that the atom takes an additional magnetic moment, directed in the opposite direction of the magnetic field and proportional to it.

As a first approximation, diamagnetism must represent atomic character and the constant associated with a molecule must be the sum of the atomic constants. This property is independent of temperature and the atomic constant and is, fixed by the number of electrons and the atomic dimensions, to an order of magnitude. Agreement with experiment is excellent and this interpretation of diamagnetism is universally accepted. Paul Langevin interpreted paramagnetism in terms of the orientation of atoms possessing a magnetic moment under the action of an external magnetic field.

The application of Boltzmann's law relating to the static distribution of such a set of atoms makes it possible to identify the following consequences:

(a) The magnetic moment and hence the paramagnetic susceptibility will depend on the absolute temperature and will vary inversely with it (a law discovered experimentally by P. Curie).

(b) Under the influence of a magnetic field of increasing magnitude a saturation of the developed magnetic moment is gradually established. The resulting relationship, known as Langevin's formula, has been found to be in very good agreement with experiment for various bodies, in particular gadolinium sulphate.

This theory made it possible to predict a remarkable phenomenon, which has been used for obtaining very low temperatures. The paramagnetic orientation must be accompanied by a rise in temperature and reciprocally an adiabatic demagnetization must result in a lowering of the temperature. By taking advantage of this latter property, de Haas was able to obtain the lowest temperatures that we know how to achieve.

The theory of the orientation of paramagnetic molecules under the influence of the magnetic field was to serve as a model, a short time later, for the dielectric theory developed by P. Debye.

Electric and magnetic birefringence

Paul Langevin applied the method of radiation that had been so successful for magnetism to give an explanation of the phenomena of electric and magnetic birefringence.

Cotton and Mouton attributed these effects to the orienting action of the fields on molecules exhibiting optical anisotropy as well as electrical or magnetic anisotropy. Using Boltzmann's law, Langevin was able to fully account for the variation of this effect with the strength of the field and with absolute temperature. This work on electric and magnetic birefringence has been the basis of much theoretical and experimental research activity on this subject.

Relativity

The negative results of the Michelson's experiments of optics and electromagnetism, undertaken to demonstrate the movement of the earth in relation to the ether or to the absolute space that it supports, could be interpreted by the contraction hypothesis of Fitzgerald and Lorentz in a satisfactory manner, without calling into question the notion of time. Paul Langevin showed that the same contraction hypothesis allowed a correct interpretation of the negative result of the Trouton and Noble experiment. Paul Langevin thus focused on the fundamental question of the relationship between mechanics and kinematics.

Mechanics, in the nineteenth century, seemed to have reached a perfect state of development, thanks to the successes achieved in astronomy. It seemed that the whole of the exact sciences were to be modeled on Newton's mechanics. These were supported by *a priori* ideas such as the concept of mass and absolute time as well as a formal distinction between the concept of mass and that of energy.

It was to the great credit of Paul Langevin to have powerfully established the interdependence between concepts considered to be distinct *a priori* and of having shown that mechanics is only a branch of physics from which it should never have separated. If one associates the principle of conservation of energy with Lorentz-Einstein kinematics, required by the laws of electromagnetism, one can fully justify the dynamics of relativity. In this new dynamic, the separation established between the concepts of mass and energy is abolished. Paul Langevin's contribution to these developments was very important; he was able to justify, by different and more general reasoning, several of Einstein's results.

Paul Langevin treated various problems relating to relativistic mechanics and in particular the discussion of Sagnac's experiment, the interpretation of the deviations of atomic masses from multiples of the mass of the hydrogen atom, etc.

By various routes, all different from those followed by Einstein, Paul Langevin obtained the new dynamic that corresponds to a new space-time and gave conclusions regarding the inertia of energy and its consequences. Among these, there was one of extreme importance: that any change in the internal energy of a system results in a change in mass, obtained by dividing the change in energy by the square of the speed of the light.

From 1913, Paul Langevin gave remarkable confirmation of this relationship by interpreting, from the inertia of the energy, the differences between atomic masses and the integer multiples of the mass of hydrogen. From the discovery of nuclear reactions, Paul Langevin quantitatively related the energies released and the variations in mass of reacting nuclei.

Ultrasonic waves

During the 1914-1918 war, Paul Langevin was led to consider a problem that maritime disasters had already posed and for which the submarine warfare carried out by the Germans made the solution very urgent: the problem of detecting submarine obstacles. C. Chilowski had suggested that a directed sound beam could be used for this purpose, using very high frequency sounds (ultrasound) so that the dimensions of the emitting source need not be too large. To transform electromagnetic vibrations into acoustic vibrations, Paul Langevin had the idea of using the piezo-electric properties of quartz discovered by Pierre and Jacques Curie. The use of the elastic resonance of quartz, and the theory of the vibration of quartz-steel assemblies, allowed the practical design of ultrasonic sounders that played a great role in the two world wars.

At the same time, a new chapter in acoustics was opened and the experiments which had been only carried out on elastic vibrations of frequencies less than about twenty thousand were made possible at frequencies of several hundred millions per second. Many discoveries in physics and many applications in chemistry and biology have thus been made possible.

On collisions between neutrons and nuclei of any mass

Shortly before the military defeat of France in June 1940, Paul Langevin tackled a nuclear physics problem concerning collisions between fast neutrons and atomic nuclei of any mass. The solution to this difficult problem was a central part in the design of devices called uranium reactors in which the neutron moderator was composed of nuclei other than light hydrogen and absorbed very few thermal neutrons. The problems associated with these developments were being studied in France at that time. The calculation concerned the probability of a fast neutron passing through a retarding medium, slowing down by successive collisions with nuclei, to reach a kinetic energy between E and $E + dE$. This problem is quite simple to solve when the mass of (the atoms in) the retarding core is equal or substantially equal to that of the neutron, but it becomes very complicated when the masses are different. By a geometrically representative investigation of the required probabilities after one, then two, then any number of collisions, Paul Langevin succeeded in giving the solution to this problem. It was the last task he successfully completed before his death.

CURRICULUM VITAE

Born in Paris, XVIIIth Arrondissement, January 24, 1872.

Died in Paris, V0 arrondissement, December 19, 1946. Buried in the Pantheon, November 18, 1948.

1884. Student of l'École Lavoisier

1888. Student of l'École de Physique et de Chimie.

1893. Student of l'École Normale Supérieure.

1897. Agrégé of physical sciences.

1897. Fellow of the City of Paris at the Cavendish Laboratory, Cambridge. 1898. Fellow of l'École Normale at the Faculty of Sciences of Paris.

1900. Laboratory assistant the Faculty of Sciences in Paris.

1902. Replacement professor at the Collège de France.

1903. Substitute professor at the Collège de France.

1905. Professor at l'École de Physique et de Chimie.

1909. Full professor at the Collège de France.

1911 to 1927. Member of the first five Solvay Physics Conferences.

1920. Scientific director of the Journal de Physique.

1926. Director of l'École de Physique et de Chimie.

1928. Chairman of the Scientific Committee of the Solvay International Institute of Physics.

1930 to 1933. Chairman of the sixth and seventh Solvay Physics Conferences.

1934. Member of the Academy of Sciences of Paris.

1945. President of the Education Reform Commission.

Doctor Honoris causa from the Universities of Manchester, Leeds, Bristol, Cambridge, Brussels, Liège. Honorary professor at the University of Buenos Aires, honorary member of the Faculty of Sciences of Santiago de Chile.

Member of the Royal Society and the Royal Institution of London. Honorary Member of the Academy of Sciences of the U.S.S.R. Member of the Royal Society of Sciences of Gottingen, of the Academy of Lincei in Rome, of the Academy of Marine, of the Academies of Sciences of Prague, Bologna, Buenos-Aires, Copenhagen, of the Royal Academy of Ireland.

Grand-Croix de la Légion d'Honneur, Commander of the British Empire.

Note 1: A full bibliography of Langevin's 126 publications was appended to the obituary, dating from 1900 to 1950, which is omitted here. Nineteen of these are on topics associated with piezoelectricity and ultrasound.

Note 2: The translation was carried out in three stages. A first good draft was generated using Google Translate. This was then edited by the first author where needed to clarify the meaning, while retaining most of the original sentence structure. The final draft was proof-read by Philippe Blondel in order to ensure accuracy where this was uncertain.

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