NOTES & RECORDS OF THE ROYAL SOCIETY

Notes Rec. R. Soc. (2012) **66**, 141–157
doi:10.1098/rsnr.2011.0049
Published online 7 March 2012

WHO KNEW PIEZOELECTRICITY? RUTHERFORD AND LANGEVIN ON SUBMARINE DETECTION AND THE INVENTION OF SONAR

by

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During World War I, submarine detection presented a strategic technological challenge, which inspired, among others, the invention of new methods and the employment of a hitherto unused scientific phenomenon. Two prominent physicists, Ernest Rutherford and Paul Langevin, independently suggested the use of this phenomenon: piezoelectricity. Yet they employed it in different ways, leading Rutherford to a useful, if limited, measuring device and Langevin to sonar. Contrary to a claim that is commonly made, Rutherford's work did not lead to sonar. These different results originated on one hand in diverging goals of the two physicists, and on the other in Langevin's more extensive knowledge of and practice with piezoelectricity, which allowed him to manipulate the crystals and contrive the novel ultrasonic design required. Nevertheless, previous encounters with the effect and prior familiarity with it were crucial for its employment by both.

Keywords: World War I; instruments; experience; knowledge transmission; technological applications

Regarded as strategically crucial, yet technologically demanding, submarine detection gained a top priority in the military research of World War I. Among others, it became a central topic for new researchers mobilized to the war research—academic physicists and electrical engineers. For many, their crucial contribution to this field and to other war-related technologies demonstrated the technological value of scientists and scientific research.[1] Not least, their unique contribution originated in their employment of knowledge and expertise acquired in their academic research to solve technological problems. In particular, scientists suggested the application of piezoelectricity, a phenomenon hitherto unused beyond the scientific laboratory, for sonar. Sonar turned out to be a highly useful and influential technology, with later consequences for modern medical scanners, and for the connected technologies of crystal frequency control and quartz clocks.

Interestingly, two physicists began using the phenomenon independently, but with different results. In Britain, Ernest Rutherford used piezoelectricity to examine the sensitivity of underwater sonic detectors. In France, Paul Langevin designed a submarine detector based on the effect, resulting in an improved method for submarine ultrasonic

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echo detection, namely sonar. Following local lore, however, Rutherford's biographers have claimed that he was 'at least the co-inventor of sonar',[2] an assertion repeated in more general histories.[3] However, this was not the case. Using archival sources including secret reports, laboratory notes, and letters, I show here that Rutherford did not invent sonar.

This paper examines the reasons for the divergence in Rutherford's and Langevin's ways of using piezoelectricity for the shared general aim of underwater detection. In particular it looks at their specific technological aims, the role of their prior knowledge and experience with the phenomenon and how they acquired it; it also analyses how these manifested in their practice. It only briefly discusses other developments in the history of underwater detection including the further research on ultrasonic methods, because extant publications, notably by Hackmann and Lelong, study them with more details.[4] The sources allow a closer reconstruction of Rutherford's research than of Langevin's. Consequently this paper focuses on the work of the former.[5] The partial comparison, suggested here, between Rutherford and his collaborator Robert W. Boyle on the one hand and Langevin on the other illuminates the work of both and instructs a fresh interpretation of their research. Langevin's research indicates the feasibility of sonar and the central properties of the novel technology, and thereby where Rutherford's group did not pursue further research. Rutherford and Boyle's case suggests the crucial ingredients that enabled Langevin's invention.

Langevin and Rutherford came to submarine research from a similar background. Both were widely respected physicists at the prime of their careers. In 1896, as 25-year-old students, the New Zealander Rutherford and the French Langevin had met in Joseph J. Thomson's Cambridge laboratory, from which they adopted methods and skills.[6] Rutherford had earned his fame in experimental research on radioactivity and the atom and in his theoretical inference from his findings. Langevin performed successful experiments on ions and discharge in gases, and also published acclaimed mathematical theoretical papers, most famously on electrodynamics and magnetism. Neither Rutherford nor Langevin worked on practical applications before the war. Nevertheless, like many physicists, both of them were mobilized to study practical questions and to improve devices for the war effort. Their wartime tasks followed military needs rather than specific connections to their earlier scientific research. Notwithstanding this, Rutherford's and Langevin's different personal scientific knowledge and experience shaped their diverging approaches to the problem of submarine detection and in particular their employment of piezoelectricity.

Rutherford's early research on underwater detection

It took the British Admiralty a year of fighting and the replacement of its First Lord to begin mobilizing its scientists for war research. In July 1915 Rutherford was nominated to the general panel of the new Admiralty Board of Invention and Research (BIR) and to its subcommittee, which dealt with submarine detection, among other things. The board saw this as a most urgent problem.[7] Rutherford was not fully happy to suspend his atomic research for submarine detection, but followed the national call. In that month he recruited two young lecturers to the new practical research: his former student Albert B. Wood from Liverpool and Harrold Gerrard from the adjoining department of electrical engineering. Wood and Gerrard joined Rutherford and his two graduate students James H. Powell and J. H. T. Roberts at the basement of Rutherford's university laboratory in

Manchester. The latter two received the BIR's financial support. Wood and Gerrard left for the Naval experimental station in Hawkcraig in November, but continued working under Rutherford's guidance until May 1916. At that time, Boyle, a physics professor and Rutherford's former student, arrived from Canada to assist Rutherford in the war research as a BIR employee. During this period Rutherford immersed himself and his small team in submarine research. Although he continued teaching a few remaining students, he had virtually no time for his prewar research on 'pure physics' until the summer of 1917.[8]

Wood recalled that during the summer of 1915, '[w]e were experimenting in a small water-filled tank with various possible sound-receivers for use under water . . .. We used a bell-type buzzer and a continuous-wave diaphragm sounder as sound sources.' Among the methods tried, 'Rutherford was hopefully, if not very optimistically, scratching small pieces of quartz crystal (with a telephone headpiece connected) to discover if the piezoelectric effect of quartz was likely to prove useful. The result of this was inevitably disappointing.'[9] By the piezoelectric effect, mechanical pressure properly directed in particular crystals produces electric polarization, or voltage differences. Rutherford tried to exploit this known property to convert sound waves—elastic vibrations—into electric waves. This might have been the earliest attempt to use piezoelectricity for practical ends. For Rutherford's biographers, however, the episode presents not only that but also the first step in his road to the invention of sonar.[10] Yet this attempt included neither of the principles of sonar: it was neither an echo system nor ultrasound (Rutherford and Wood employed sonic frequencies and the detection was based on audible vibrations transmitted through the headpiece).

By September, after examining the known detection techniques, Rutherford concluded that locating a submarine 'by its own characteristic sounds when in motion' would be the most promising method. Indeed, this technology, which had already been employed by the British navy, was the only one that would be used in action during the war. However, its yield was very limited.[11] Consequently, Rutherford and his team in Manchester and Hawkcraig experimented with different kinds of 'hydrophones'—detectors of underwater sound. During the second half of 1915 and 1916 they followed two major lines of research, both relating to 'passive' receivers of audible sound. In the first they examined the underwater behaviour of different diaphragms and microphones informed by the mathematical theory of Horace Lamb. The second line of inquiry included testing, improving, designing and constructing particular hydrophones. Designing receivers sensitive to the direction of sound occupied much of Rutherford's attention, leading, among other results, to a joint patent with another established physicist William H. Bragg, who at that time headed the BIR's experimental station.[12]

Ultrasonic echo method

Among the methods dismissed by Rutherford as impracticable was Reginald Fessenden's sonic echo method, suggested in 1912 to locate icebergs. In this method, whose general idea was independently suggested by a few inventors, one detects obstacles by sending sound waves and receiving their reflection from submarine objects. This is an active method, because the seeker is actively emitting signals for locating the submarine object; by contrast, in a passive method, such as the use of a hydrophone, one depends on signals emitted by the sought object. Tactically, an active system can allow more flexibility in use, in particular in moving vessels. However, in 1915 the question was whether a practical active system was feasible, and Rutherford, like most, thought that it was not. Rutherford and the British did not know of Constantin Chilowsky's suggestion to replace the sonic by ultrasonic waves, already under investigation in France.

Chilowsky, a Russian émigré in Switzerland, an independent inventor who studied physics in German Strasbourg, saw two major advantages of ultrasonic over sonic waves for echo detection: (i) the ratio between their length and the surface of the emitter permits a relatively small angle to be used for the pencil beam of the waves, enabling the direction of the obstacle to be determined, and (ii) the narrow pencil beam results in relative energy efficiency because it is not dispersed in all directions.[13] However, the efficient production and detection of ultrasonic waves raised a technological challenge. In February 1915 Chilowsky sent his proposal, which included a magnetic method for producing the waves, to the French authorities, who forwarded it to Langevin. Langevin doubted the feasibility of the magnetic emitter and instead designed a new electrostatic transducer—'a singing condenser'. Working in close collaboration with the navy in Paris and in Toulon, Langevin and Chilowsky experimented with this emitter, using a regular carbon microphone as a receiver. The emitter was composed of a slim metallic slab that vibrated as a result of the electrostatic force exerted on it by a nearby thicker metallic plate connected to a source of alternating current. An insulator, such as a mica bar, was put between the plates.[14]

In May 1916 the French revealed the system to a few British scientists and engineers who visited France. Beginning in early 1916, such visits were the central method for exchanging technical–scientific information between the two allies, until the appointment of formal resident liaison officers in October of that year.[15] Rutherford expressed doubts. '[T]he methods of production of high frequency sound by Langevin and Chilowsky', he wrote to Bragg, 'seem interesting and important, but I think it will probably take a long time to bring them to a really practical issue.'[16] Nevertheless, in August the British began their own research on the ultrasonic echo method, exploring alternative techniques of producing ultrasound. The BIR sent Boyle, Rutherford's collaborator, to conduct the research in London, in the private laboratory of the electrical engineer, inventor and industrialist Sidney G. Brown.[17] Rutherford himself continued studying sonic hydrophones. Boyle regularly briefed Rutherford, his mentor and the leading scientific authority in the submarine committee, about the research on alternatives to Chilowsky and Langevin's singing condenser and carbon microphone.

The design of Rutherford's piezoelectric device

During the summer and autumn of 1916 Rutherford's team tried to determine the efficiency of their microphones and diaphragms; that is, the ratio between the amplitude of the underwater sonic waves and the signals that they emitted. Thus, they needed to measure amplitudes of vibrating diaphragms, which they assumed to be equal to those of the sound waves.[18] The assumed amplitudes of the sound waves (10^{-6} to 10^{-8} cm), however, were two to four orders of magnitude smaller than the sensitivity of common optical techniques for their measurement, suggesting the need for a new method. Rutherford saw a possible solution in piezoelectricity, in which a small mechanical amplitude can generate observable electric voltage. He presented his ideas in a 'preliminary note about a

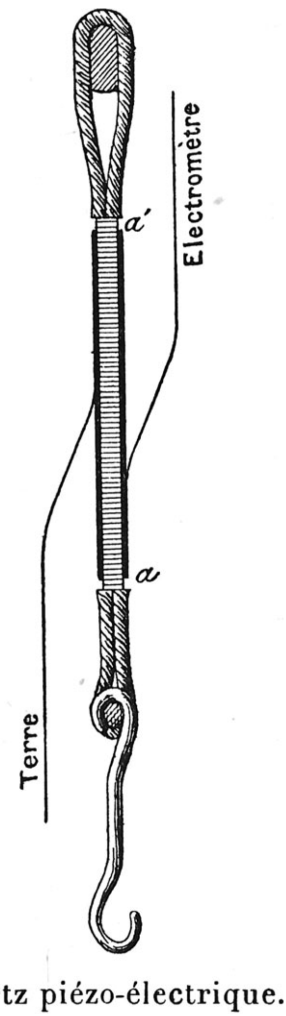

Figure 1. The Curies' '*quartz piézo-électrique*' as used in their original instrument. (From Pierre Curie, *Œuvres de Pierre Curie* (Gauthier-Villars, Paris, 1908), p. 557.)

novel method of measuring the amplitude of vibration of a diaphragm and the generation of underwater supersonic waves' on 28 September 1916.[19]

At the heart of Rutherford's method lay a specific device—the 'quartz piezo-electrique' (his term)—whose properties shaped its later use. Originating in Jacques and Pierre Curie's 1882 instrument for measuring either electric charge or pressure, the device consisted of a long and narrow quartz plate or bar (say 100 mm × 20 mm × 0.5 mm), whose two larger surfaces were metallized. The Curies used the particularities of 'transverse' piezoelectricity in quartz—the strain due to electric voltage along a perpendicular direction—in which the resulting elongation of the crystal per volt is proportional to the ratio between the crystal's length and thickness (namely 100:0.5) (figure 1). Following the

Curies' design, Rutherford firmly fastened one end of the crystal, leaving the other free to move, or vibrate lengthways, in response to alternating current.

Rutherford suggested three uses of the 'quartz piezo-electrique', of which only the first would be applied. In the first, the plate's free end is attached to a microphone or a diaphragm, and thus produces elastic vibrations at the surface of the microphone. By connecting the microphone to a separate circuit, the experimenter can determine the minimal voltage on the quartz sufficient to produce a vibration detectable by the microphone. Using piezoelectric theory and empirical data one can calculate from the voltage the expansion of the quartz, and hence the assumedly equal amplitude of the microphone's vibration. In the second method the 'piezo-electrique' is used to balance the sound produced by a source unconnected to the receiving system. As with the previous method, the known value of the piezoelectric coefficient allows one to calculate the amplitude of the crystal's vibrations and thus the amplitude of the underwater sound waves.

The third method departed from Rutherford's main research. It employed the device to produce waves rather than to measure them, and it dealt with ultrasonics. Rutherford suggested generating underwater ultrasonic waves by connecting the electrodes of the 'piezo-electrique' plate to a high-frequency source, such as the common Poulsen arc. A small plate rigidly connected to the free end of the quartz, and exposed on one side to the water, would communicate the ultrasonic vibration to the medium. Because the power communicated by one plate was low, Rutherford suggested multiplying the effect by connecting a few bars in parallel to the same power source. Although he believed that this arrangement would be generally efficient, he admitted that the 'actual energy communicated to the water will be comparatively small.' This is the first recorded suggestion to employ piezoelectricity for the production of supersonic waves, but it is far from sonar. In comparison with the later method, it lacked any reference to echo detection, and consequently any suggestion for a receiver. Rutherford's device could be used for other ends such as underwater signalling, a possibility that he had mentioned earlier.[20] This was Rutherford's second attempt to employ the effect beyond a measurement device. Yet, as with the earlier abovementioned attempt to use the effect for sound detection, he did not progress to make a practical device. A comparison of Rutherford's emitter with Langevin's later device, which differed in the crystal cut and oscillation modes, merely highlights the inefficiency of the former emitter, inefficiency that Rutherford had already acknowledged.

The origins of Rutherford's proposal

Searching for a method to measure tiny vibrations of his microphones, Rutherford found a solution in piezoelectricity. However, to apply piezoelectricity, familiarity with the effect and its experimental manifestations was required. Moreover, as mentioned, Rutherford employed a particular device that used piezoelectricity in a specific way, rather than designing a new instrument. His application of the phenomenon therefore depended on his familiarity with the Curies' 'piezo-electrique balance'. However, this device was not well known in the scientific world; in technological circles it was almost unheard of.[21] Although detailed information about the device appeared in publications that were accessible to most scientists, most did not look for that knowledge.

Rutherford himself had encountered the piezoelectric measuring instrument through research on radioactivity. In 1898 Marie Curie introduced a 'quartz *piézo-électrique*' balance to determine the weak charges radiated from the small samples at her disposal, probably following the advice of her husband, Pierre.[22] The method had rarely been used previously,[23] and remained a specialty of Curie's laboratory also in the research into radioactivity. It remained a local experimental knowledge. Most probably Rutherford did not use the method himself, because none of his own or his collaborators' research papers on radioactivity mention it. Yet he closely followed the Curies' research, the main competition to his own. Moreover, he did describe 'measurement by means of the quartz piezo-electrique' in his 1904 and 1913 textbooks, in which he followed Marie Curie's publications.[24] To explain the use of the 'quartz piezo electrique' to his reader, Rutherford had to have a thorough understanding of the method, although not necessarily full mastery of the procedure. Thereby he became more familiar than most physicists with the piezoelectric device and its phenomena.[25]

The knowledge of the 'quartz piezo-electrique' thus followed a personal and contingent path from Jacques and Pierre Curie through Marie Curie to Rutherford. In her early experimental research, Marie followed instruments and methods previously employed by Pierre. This suggests that he introduced his wife, a doctoral student at the time, to the use of the piezoelectric device, which he had invented with his brother a decade earlier.[26] Although the personal contact helped in directing the young researcher to this uncommon method, by reconstructing Marie's experiment on radioactivity Boudia and Molinié have shown that it was unnecessary for mastering the quartz and the electrometer.[27] The tacit knowledge required to work with the apparatus was either shared by contemporary experimentalists or could be easily acquired by working with the 'quartz *piézo-électrique*'. Nevertheless, contemporary researchers who lacked a personal connection to the inventors of the balance did not employ it. This suggests that, at least in some cases, the obstacles to the adoption of an experimental method do not originate in difficulties in gaining non-verbal knowledge needed for commanding the laboratory settings. Awareness of the possible benefits of a new method seems more important than obstacles to gaining tacit knowledge for the adoption of an experimental device such as the piezoelectric balance.

For his vibrating quartz, Rutherford did not need even to master the '*piézo-électrique*', as Marie Curie did. Unlike the case with complex experimental apparatus,[28] Rutherford did not need to learn a technique from those who had mastered it before. Moreover, Rutherford did not replicate the Curies' use, because he modified the device for his own aim. His originality lay in applying an alternating voltage of thousands of cycles per second to the 'quartz piezo-electrique'. Thereby he departed from earlier static or semi-static measurements. He also departed from previous scientific study of piezoelectricity, because no experiment had been conducted on oscillating crystals. Rutherford therefore argued for the validity of the law, which had been found for static cases, also in the dynamic case used in his apparatus. Thus he extended the empirically confirmed laws to the latter domain.

Although Rutherford's device went further than the Curies', its origins in this predecessor limited its use as a supersonic generator. Rutherford turned a static device into a dynamic one, but it remained a measuring instrument. This device was highly sensitive to changes in voltage and was thus useful for his primary aim of determining amplitudes of underwater diaphragms. High sensitivity, however, was not useful for producing underwater waves. Although large amplitude is important for a measuring instrument, in contrast high energy (or, more precisely, power) is needed to generate waves. In his suggestion to use the instrument as a generator, however, Rutherford kept the Curies' crystal cut, which gave high sensitivity but low power, rather than rethinking the design on the basis of the requirements for an ultrasonic emitter, as Langevin would do. He acknowledged that the device could communicate only a small amount of energy, but he did not depart from the Curies' basic design, and thus proposed only an inefficient generator.[29]

The use of Rutherford's device

Contemporary documents, including a laboratory notebook, correspondence and reports,[30] show that Rutherford and his collaborators in Manchester and London constructed two devices according to his proposal and used them to study diaphragms and microphones. However, they show no hint that they applied the 'quartz piezo-electrique' to generate supersonic waves.

For about a week in October–November 1916, Rutherford, his laboratory assistant William Kay, Powell and Roberts experimented with the 'quartz piezo electrique', at the laboratory of Manchester University. They examined the minimal amplitude detectable by an underwater diaphragm and a microphone at frequencies of about 1000 Hz (soprano pitch), following the first method suggested by Rutherford. They detected vibrations either directly, when the other side of the diaphragm was in air, or through the microphone, probably by means of a telephone earpiece.[31] Their general laboratory skills allowed them to produce the experiment without direct contact with earlier users of the 'piezo-electrique'. Rutherford was satisfied with the results, writing to Bragg: 'the quartz piezo-electrique works like a charm. At a frequency of 1000 I can detect a condensation [relative change of the wave density] of 10^{-11} while 10^{-10} gives a sound that anyone could hear at once in a moderately quiet room.'[32] The experiment supported Rutherford's belief that sensitive sonic receivers would detect submarine engines. Bragg was 'delighted to hear about the piezo-electrique, it sounds most useful', and recommended its use for examining how electrical and sound signals are related in microphones and diaphragms to other researchers of the BIR.[33]

The Mancunian team did not experiment with ultrasonic frequencies. Rutherford sent a second crystal plate (which Maurice de Broglie, the French scientific attaché to the British Admiralty, had brought from Paris in response to Rutherford's request) to Boyle in London for ultrasonic experiments.[34] In early December 1916, Boyle determined the minimal alternating voltage on the crystal that led to amplitudes detectable by the microphones. With his assistant and Brown's employee, B. S. Smith, he modified the settings for the needs of ultrasonics (figure 2).[35] Boyle and Smith could not replicate Rutherford's success. The high frequencies led to interference from the electromagnetic waves produced by the instrument. Moreover, they found 'that the piezo effect per volt $\left(\propto \text{to say} \frac{\text{current in galv. due to piezo}}{\text{voltage on Quartz}}\right)$ falls as the frequency goes up.' Because of these problems they failed to use the instruments in frequencies above 31 000 Hz. This cutoff was significantly lower than in their studies of microphones by other means.[36] There is no hint that Boyle and Smith tried to further improve the experimental setting to reach higher frequencies. They probably did not dedicate more than two weeks to the measurements with the piezoelectric device, for these pertained only to a measurement of one aspect of the echo method system that they were studying. In their goal-directed research on methods to emit ultrasounds they had no time to dwell with such a side issue. By January 1917 the 'piezo-electrique' was waiting to be sent back to Rutherford, who was in no hurry to get it.[37]

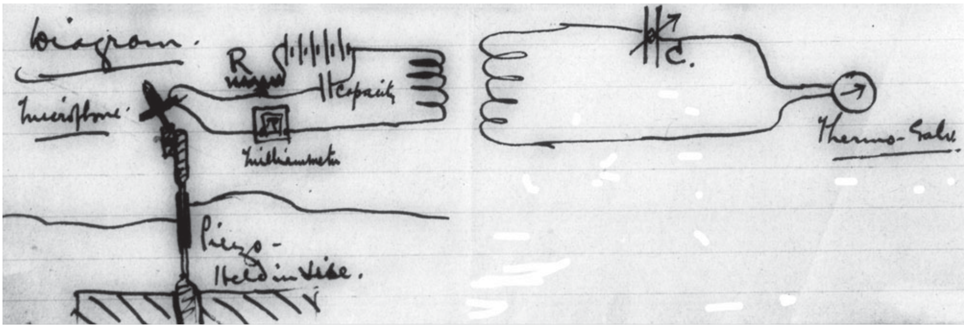

Figure 2. Boyle's drawing of his measurement with the piezo-electrique (on the lower left side), which is connected to a microphone. The microphone, which forms part of an *RCL* circuit on the left, generates alternating current in the circuit as a result of its mechanical movement. Through the coils this current induces an electric current in the *CL* circuit to the right; a thermoelectric galvanometer is used to measure the current. (From Boyle to Rutherford, 12 December 1916.)

Boyle and Smith showed much interest in piezoelectricity. 'There can be quite a bit of work done on the "piezo",' Boyle wrote to Rutherford, 'but', he added, 'after the war.'[38] Clearly, Boyle did not attempt to employ the phenomenon for the very technological problem he was trying to solve—the transmission and reception of underwater ultrasonic waves—although he did examine quite a few solutions to the problem. Initially, Boyle and Smith had attempted to produce and receive underwater ultrasound by electromagnetic methods. However, in November 1916 they concluded that the production of high-frequency waves 'by electro-magnetic apparatus of this design, is not possible.' Consequently they turned to 'Electro-dynamic and electrostatic methods',[39] and even examined mechanical methods; all, however, were without much success.[40] Despite Rutherford's suggestion of employing piezoelectricity for the production of ultrasonic waves, Boyle did not explore the use of the 'piezo' for this end. Boyle would do so only after Langevin's success, and then would learn the method in Langevin's laboratory.

Boyle and Smith's failure to explore a piezoelectric method can be explained by the low power output of the emitter purposed by Rutherford, but also by their superficial knowledge of the effect. In addition, their problematic experience with the quartz plate at high frequencies militated against using it to generate waves at those frequencies. Even on paper, Rutherford's piezoelectric generator was inferior to other methods. As a receiver it seemed much less sensitive than their microphones. They never really viewed the piezo system as a transducer. To make it an efficient transducer required good knowledge of the phenomenon and preferably experience in handling these crystals. Boyle and Smith lacked both. Boyle, the more knowledgeable of the two, had learnt the basics of piezoelectricity only after his work on the 'piezo' and continued to show rudimentary knowledge of the phenomenon.[41] In principle, Boyle and Smith could have gained better command of the effect from printed sources, but that would have required much time for locating and learning the relevant knowledge and thus a prior belief that the phenomenon might be valuable for their research. Such a belief, however, required a thorough acquaintance with the phenomenon.

At a secret inter-allied meeting in October 1918, after experimenting for more than a year with Langevin's piezoelectric device, Boyle candidly described the British research:

> The utilization of the piezoelectric properties of quartz was introduced to England not at all for ultrasonics, but for measuring the amplitudes of certain mechanical movements . . .. Rutherford followed his method of measuring amplitude and suggested the possibility of obtaining ultrasonic vibrations . . .. But to be totally frank, it should be said that we undertook nothing similar [to Langevin's work] in England since we did not know the amplifiers of high power.[42]

One should not, however, uncritically accept Boyle's explanation for undertaking 'nothing similar'.[43] Granting the claim that the British did not have powerful amplifiers, the above analysis shows that the British did not reach a point where better amplifiers would have made a difference. Valve amplifiers, to which Boyle referred, were unnecessary for transmitters, for which other devices (such as a Poulsen arc) could and did produce powerful electric oscillations. Whereas valve amplifiers had a crucial role in Langevin's receivers, the British did not even suggest the use of piezoelectricity for that end. Moreover, the British, including Boyle himself, had not been as ignorant about electronic valves as he suggested. Shortly *before* their above-mentioned experiments, Boyle and Smith experimented with a circuit in which a 'valve relay can be used to rectify the signals and to produce beats of audible frequency by interference with supersonic vibrations. The same valve can also be employed to magnify the received signals, and in this way to increase the sensitiveness.'[44] Boyle and Smith probably employed either valves designed by the French military telegraphy, which had been regularly produced in Britain from 1916, or a British modification of them. The performances of the valves produced in the two countries, and of multi-valve amplifiers based on these, were similar, and clearly did not present a qualitative difference that would have prevented an attempt to employ British valves for a piezoelectric receiver and emitter.[45]

The French 'hard' valve employed a high vacuum, whereas earlier 'soft' valves used in Britain depended on small quantities of gas in the tube. 'Hard' valves were more stable and easier to handle than 'soft' valves, a fact of high significance in the battlefield. 'Soft' valves, however, were more sensitive and could be used by trained technicians on board a vessel or offshore, and thus for detecting submarine signals. Indeed, in March 1916, the BIR panel, of which Rutherford was a member, received a report on 'valves for submarine sound amplification'. This was one in a series of reports on the use of thermionic valves, discussed in the BIR from December 1915.[46] Yet Rutherford had most probably already known about soft-valve amplifiers, among others, from J. J. Thomson, a member of the BIR central committee and Rutherford's former teacher, who supervised the development of soft valves at his Cavendish Laboratory.[47] It is therefore highly unlikely that Rutherford and his associates were ignorant of strong amplifying valves in September 1916; they certainly used valves two months later.

Langevin's piezoelectric sonar

Whereas Rutherford introduced piezoelectricity for the improvement of hydrophones, Langevin employed the effect to improve the method of ultrasonic echo detection. Since learning about Chilowsky's suggestion, Langevin had focused his research on developing ultrasonic echo techniques. In spring 1916, as a result of disagreements with Langevin, Chilowsky left the research, leaving the French physicist in full charge. Langevin divided his time between Paris and Toulon, where Marcel Tournier, his assistant from the École de Physique et de Chimie Industrielles (EPCI), conducted research in his absence. By early 1917, Langevin had dispensed with the metallic sheet of the original ultrasonic emitter, relying instead on the electrostatic properties of seawater. His new and more efficient 'mica emitter' consisted of a metallic plate subjected to alternating current of the desired frequency mounted on a mica condenser used as an insulator and immersed in the water. It so impressed the British that in April 1917 they decided to copy and improve on the French design rather than designing alternative methods as they had hitherto done.[48]

In the meantime, however, Langevin turned his attention also to the ultrasonic receiver, which until then had seemed to be the simpler part of the system. Yet his *in situ* experiments showed him that 'the [carbon] microphone gave very irregular results, and required delicate regulations in order to keep the sensibility of the carbon contacts approximately constant against the variations in outside pressure due to the movement of the sea.'[49] The realization of the problem followed the advancement of the French research at sea, with the collaboration of the navy. Looking for an alternative, in February 1917 he employed a slim quartz sheet, connected to an electric circuit as a receiver. Unlike Rutherford, Langevin did not rely on the Curies' instrument. Instead, he employed a crystal of very different dimensions. He used a square instead of a long, thin rectangular sheet, cut in a plane perpendicular to the cut of the crystal in the 'quartz-balance' (a large surface in the *yz* rather than the *xz* plane, in common symbolism). With this cut, he employed the longitudinal effect in quartz, namely the generation of electric voltage along the direction of the changes in pressure (and vice versa), rather than a transverse effect. This design, which allowed a much larger surface to vibrate with changes in water pressure, considerably increased the sensitivity of the plate to ultrasonic waves. Unlike a claim in the secondary literature, it allowed Langevin to obtain the required quartz sheets from common crystals.[50] In addition, he benefited from French advances in vacuum tube amplification used in radio (also available, as already mentioned, in Britain), which facilitated the detection of the feeble electric signals emitted by the quartz plate.

In April, encouraged by the success of the receiver, Langevin modified the device for use also as a transmitter. He employed elastic theory to devise a thicker plate that would be a better piezoelectric transmitter because it resonated at a frequency desired for submarine detection. To this end he used a 'crystal of exceptional size and purity', obtaining a few sheets 'of about a square decimetre of surface, and of fifteen millimetres thickness'. Later in that year he contrived a steel–quartz mosaic 'sandwich' to obtain the same 'piezoelectric and elastic properties from easily available crystals'.[51] After Langevin's early success with the piezoelectric transducers, the French informed their allies about the details of the research, which was consequently pursued by British, American and Italian groups. Nevertheless Langevin's group continued to lead, even though its transducers would also not go into service before the war had ended.

Whereas Rutherford learnt about the use of piezoelectricity from publications, Langevin enjoyed a direct personal contact with the Curies, which included the observation and probably manipulation of piezoelectric crystals. Pierre's long and lasting influence on Langevin dated to the latter's earliest training in academic physics at Curie's laboratory of the EPCI. In 1888, when Langevin entered the school, Curie still conducted research related to piezoelectricity, which he had discovered with his brother Jacques in 1880. He also furnished its laboratory with related pieces of apparatus, including a piezoelectric balance electrometer.[52] In 1905 the device, along with the physical laboratory, came under the responsibility of Langevin, who succeeded Curie as a physics professor at the school. Earlier, during the 1890s, Langevin had developed a close friendship with the Curies and kept up with their research on radioactivity.[53] According to his recollections, back in 1915 he had already considered a piezoelectric ultrasonic sender, although he did not pursue the idea until after he had found problems with his receiver in late 1916. Shortly thereafter, Langevin was informed about Rutherford's general idea, and this may have encouraged him to pursue his own piezoelectric method.[54] Still, the comparison with Rutherford and his team suggests that Langevin enjoyed a more thorough knowledge of the phenomenon in its experimental manifestations, which enabled his success. His familiarity with various manifestations of piezoelectricity, especially with different cuts and directions of the effect, allowed him to think flexibly about its uses and to apply it for his needs.

Conclusions

Rutherford considered passive reception of the noise from U-boats as the most promising method for their detection, and therefore concentrated his efforts in developing such methods. Looking for ways to answer a particular question that emerged in this research, he exploited and modified the Curies' piezoelectric quartz to measure small mechanical vibration. His piezoelectric instrument and his acquaintance with the effort to produce ultrasonic waves inspired his suggestion to employ the instrument as an ultrasonic emitter. However, with regard to his preference for the passive system, he considered the problem of ultrasonic emission only briefly, and did not work on the realization of his proposal. Contrary to the claim of Rutherford's biographers, his suggestion was far from sonar. Langevin, in contrast, became the champion of the ultrasonic echo method and immersed himself in its development. His invention of the piezoelectric sonar resulted from a concentrated effort to solve specific problems: ultrasonic reception and then emission. His success highlights the importance of framing precise technological aims. It also shows the crucial role of actual research towards a technological aim, research that often reveals unforeseen problems such as the effect of the sea on the carbon microphone. In so far as Langevin's commitment to the echo method resulted from his personal identification with a technology in which he had invested his time and prestige, the case also points to the power of such personal interests in guiding scientists' research.

By following the Curies' measuring instrument, Rutherford succeeded in swiftly designing and constructing a dynamic measuring instrument. Considering his limited practice with piezoelectricity, restricting his efforts to the extant instrument was a wise move. Yet in so doing he limited himself to the particularities of that instrument, precluding the use of piezoelectricity for an efficient sonar system.[55] Rutherford's lack of experience with the various manifestations of piezoelectricity discouraged him from exploring beyond the restrictions of the particular device at hand, even when he did consider its use to a novel end. Langevin, better acquainted with the effect on its experimental and theoretical aspects, more easily transcended the Curies' design, and suggested a novel method that enabled a breakthrough.

Notwithstanding the differences between them, the fact that Rutherford and Langevin, two physicists with previous encounters with piezoelectricity, were the only ones who proposed its use for practical ends suggests that prior familiarity with the phenomenon enabled its novel technological application. Even though researchers could have acquired the knowledge needed for applying the effect without a direct connection with those who had already worked in the field, a previous encounter with the effect still seems to have been a prerequisite for considering its practical use. Rutherford's and Langevin's acquaintance with the phenomenon placed it on their horizons and thereby made it a candidate for application. Boyle's obliviousness to the potential utility of piezoelectricity well exemplifies the crucial role of previous knowledge of phenomena, not so much in acquiring knowledge to master the effects, as in recognizing their possible use and benefits. In principle Rutherford could have examined further manifestations of piezoelectricity that were potentially more useful for ultrasonic transducers. Yet the case suggests that in practice scientists prefer to stay closer to methods and knowledge with which they are familiar, rather than look for solutions in areas in which they are less so, such as other piezoelectric cuts for Rutherford and Boyle. Langevin's earlier extensive knowledge of and practice with piezoelectricity provided him with resources for considering the manipulation of the crystals needed for sonar. The critical contribution of previous familiarity with the phenomena indicates the role of contingent, often personal, routes by which knowledge is transmitted, as exemplified by Langevin's connection to the Curies and the coincidence of their and Rutherford's interest in radioactivity.

Acknowledgements

I am grateful to the Alexander von Humboldt foundation for a fellowship that allowed me to enjoy the hospitality of the Max Planck Institute for the History of Science, and which enabled the research for this paper; to Catherine Kounelis and James Nye for their help in the archives; to Jeremiah James, Ed Jurkowitz and Jaume Navarro for their thoughtful comments on earlier versions of the paper; and to Robert Fox and the anonymous referees for their helpful editorial suggestions.

Appendix A. Archival sources

In the research towards this paper I have used documents from the following archives: Department of Manuscripts & University Archives, University Library, Cambridge (CUL), papers of Ernest Rutherford and Joseph J. Thomson; UK National Archives (UKNA): Records of Admiralty, Naval Forces, Royal Marines, Coastguard, and related bodies; La Centre de resources historiques de l'École Supérieure de Physique et de Chimie Industrielles de la Ville de Paris, papers of Paul Langevin (ESPCI).

In the following I give the details and locations of the documents mentioned in the text, ordered by kind and date.

Reports

Rutherford BIR 30 September 1915: 'Report on methods of collection of sound from water and the determination of the direction of sound', papers of John William Strutt, Lord Rayleigh, CUL MS.Add.8243/2.

Boyle BIR 9 September 1916: 'Attempts to transmit and receive supersonic vibrations' (BIR 10833/16), UKNA ADM 293/5.

Rutherford BIR 28 September 1916: A French translation from 23 January 1919 of Rutherford's note to the BIR from 28 September 1916 (BIR 11738/16), in a letter of A. Grasset to P. Langevin, 23 January 1919. ESPCI L138/153; my translation is informed by mentions of the note in later British reports and terms used in Rutherford–Boyle correspondence.

Boyle BIR 23 November 1916: 'Production and reception of high-frequency sound waves by the method of the Brown grid magnetophone' (BIR 14243/16), UKNA ADM 293/5.

Boyle and Smith BIR 28 November 1916: 'Reception of high frequency sounds by microphones' (BIR 14244/16), UKNA AMD 293/5.

Rutherford BIR 18 December 1916: 'Sensibility of diaphragms for reception of sound from water' (BIR 15239/16), UKNA ADM 218/14.

BIR 31 December 1916: 'Report of proceedings to 31st December 1916', Royal Naval Museum Library, MSS 252/13/62.

Boyle BIR 1 August 1917: 'Report of mission to France for the Admiralty Board of Invention and Research—March 20th to July 19th, 1917' (BIR 30061/17), UKNA ADM 293/10.

Boyle 19 October 1918: 'Conférence interalliée du 19 octobre 1918: Compte rendu officiel—expose du Docteur Boyle', ESPCI L194/09.

Wood (name added in handwriting) BIR 12 December 1918: 'Comparison of valves—French, British and German', UKNA ADM 218/282.

Correspondences

All the correspondences of Rutherford used here, expect those with Bragg and Paget, are found in CUL Ernest Rutherford papers. A copy of these letters is available also in the Archive for the History of Quantum Physics.

Rutherford–Bragg and Rutherford–Paget correspondence in 'Rutherford File', UKNA ADM 212/157.

Further letters

de Broglie to Langevin, 23 December 1918, ESPCI L194/50, including an extract from a letter of Rutherford to de Broglie from 25 October 1916.

Langevin to de Broglie, 27 December 1918, ESPCI L194/50.

Notebooks

Rutherford Notebook 19, CUL MSS.Add.7653:NB.19.

Original French manuscripts for published translations in ESPCI

Paul Langevin, 'Echo sounding', *Hydrogr. Rev.* **2**, 51–91 (1924); original French (without the first page, probably an advanced draft) L194/28.

Paul Langevin, 'Conference Intèralliée sur la recherché des sous-Marine par la méthode ultra-sonore: historique des recherches effectuées en France' (19 October 1918), L196/16; English translation in David Zimmerman, 'Paul Langevin and the discovery of active sonar or asdic', *North. Mariner* **12**, 39–52 (2002).

Notes

1 Daniel J. Kevles, *The physicists: the history of a scientific community in modern America*, 2nd edn (Harvard University Press, Cambridge, MA, 1995); Guy Hartcup, *The war of invention: scientific developments, 1914–18* (Brassey's Defence Publishers, London, 1988).

2 David Wilson, *Rutherford, simple genius* (MIT Press, Cambridge, MA, 1983), pp. 373–375; John Campbell, *Rutherford: scientist supreme* (AAS Publications, Christchurch, New Zealand, 1999), p. 371.

3 John L. Heilbron, *Ernest Rutherford and the explosion of atoms* (Oxford University Press, 2003), p. 94; Helge Kragh, *Quantum generations: a history of physics in the twentieth century* (Princeton University Press, 1999), p. 134.

4 Willem D. Hackmann, *Seek & strike: sonar, anti-submarine warfare and the Royal navy, 1914–54* (Her Majesty's Stationery Office, London, 1984); Benoit Lelong, 'Paul Langevin et la détection sous-marine, 1914–1929. Un physicien acteur de l'innovation industrielle et militaire', *Épistémologiques* **2**, 205–232 (2002).

5 Another reason for this focus is the need to correct, as mentioned, a distorted picture of Rutherford's research, whereas I find no similar need for Langevin's case.

6 Benoit Lelong, 'Ions, electrometers, and physical constants: Paul Langevin's laboratory work on gas discharges, 1896–1903', *Hist. Stud. Phys. Biol. Sci.* **36**, 93–130 (2005).

7 Roy M. MacLeod and E. Kay Andrews, 'Scientific advice in the war at sea, 1915–1917: the Board of Invention and Research', *J. Contemp. Hist.* **6**, 3–40 (1971).

8 A. B. Wood, 'From Board of Invention and Research to Royal Navy Scientific Service: reminiscences of underwater-sound research, 1915–1917', *Sound: Its Uses Control* **1** (3), 8–17 (1962). On the support to Powell, Roberts and Boyle, see Rutherford to Paget, 3 April 1916. An early mention of Boyle's work within the group is in Rutherford to Bragg, 12 June 1916. Rutherford's correspondence and the number of his reports testify to the intensity of his submarine research. See also Jeff Hughes, 'William Kay, Samuel Devons and memories of practice in Rutherford's Manchester laboratory', *Notes Rec. R. Soc.* **62**, 97–121 (2008), at pp. 112–114. Notice that the dates given by Kay are somewhat inaccurate. Kay reports on Rutherford's attitude to war research. In the same vein Rutherford wrote to Bragg (23 May 1916): 'It is a pity that it is so difficult for us [British] now to devote our attention to the pure science problems.' For details and locations of archival sources see Appendix A.

9 Wood, *op. cit.* (note 8), p. 10.

10 Wilson, *op. cit.* (note 2), p. 373; Campbell, *op. cit.* (note 2), p. 371.

11 Rutherford BIR 30 September 1915, p. 8; Wilson, *op. cit.* (note 2), pp. 346–347. On the actual yield of the hydrophones, see Hackmann, *op. cit.* (note 4), pp. 69–71.

12 Hackmann, *op. cit.* (note 4), pp. 51–54; Bragg–Rutherford correspondence, Wood, *op. cit.* (note 8), pp. 12–13; Campbell, *op. cit.* (note 2), p. 369.

13 Igor I. Klyukin and E. N. Shoshkov, *Konstantin Vasil'evich Shilovskii 1880–1958* (Nauka, Lenigrad, 1984), pp. 41–42 and 46–50 [in Russian]. I thank Oksana Kuruts and Alexei Kojevnikov for their help with the Russian.

14 Paul Langevin, 'Conference Intèralliée sur la recherché des sous-Marine par la méthode ultra-sonore: historique des recherches effectuées en France' (19 October 1918), L196/16; an incomplete English translation is given in David Zimmerman, 'Paul Langevin and the discovery of active sonar or asdic', *North. Mariner* **12**, 39–52 (2002); Frederick V. Hunt, *Electroacoustics: the analysis of transduction, and its historical background* (Harvard University Press, Cambridge, MA, 1954); Constantin Chilowsky and Paul Langevin, *Procédés et appareils pour la production de signaux sous-marins dirigés et pour la localisation á distance d'obstacles sous-marins*. French Patent 502913, filed 29 May 1916, granted March 1920.

15 For the status of the cooperation see Hackmann, *op. cit.* (note 4), pp. 39 and 84; BIR 8 June 1916, 31 December 1916, p. 4.

16 Rutherford to Bragg, 20 June 1916.
17 BIR 31 December 1916, p. 21; Rutherford to Bragg, 12 June 1916; Boyle BIR 9 September 1916, 23 November 1916; Boyle 19 October 1918, Hackmann, *op. cit.* (note 4), p. 84.
18 Rutherford to Bragg, 12 June 1916. See also the letters of 27 September and 5 November, and Rutherford BIR 18 December 1916.
19 BIR 28 September 1916. I could only locate a French translation of the original report.
20 Rutherford BIR 30 September 1915, p. 2.
21 Philippe Molinié and Soraya Boudia, 'Mastering picocoulombs in the 1890s: the Curies' quartz-electrometer instrumentation, and how it shaped early radioactivity history', *J. Electrostat.* **67**, 524–530 (2009).
22 Soraya Boudia, *Marie Curie et son laboratoire, science et industrie de la radioactivité en France* (Éditions des Archives Contemporaines, Paris, 2001), pp. 58–61; Shaul Katzir, *The beginnings of piezoelectricity: a study in mundane physics* (Springer, Dordrecht, 2006), pp. 214–215.
23 To my knowledge, only Jacques Curie had used it in research: Jacques Curie, 'Recherches sur le pouvoir inducteur spécifique et la conductibilité des corps cristallisés', *Annls Chim. Phys.* **17**, 385–434 (1889).
24 Ernest Rutherford, *Radio-activity* (Cambridge University Press, 1904), p. 89; Ernest Rutherford, *Radioactive substances and their radiations* (Cambridge University Press, 1913), p. 104.
25 Only few books provided an explanation of the instrument. In addition to Rutherford's and Curie's books on radioactivity, the 'quartz piezoelectrique' was mentioned in Stefan Meyer and Egon R. von Schweidler, *Radioaktivität* (Teubner, Leipzig, 1916).
26 Bodia, *op. cit.* (note 22), pp. 47–64.
27 Molinié and Boudia, *op. cit.* (note 21).
28 Harry M. Collins, *Changing order: replication and induction in scientific practice* (SAGE, London, 1985), pp. 51–78; J. L. Heilbron and Robert W. Seidel, *Lawrence and his laboratory: a history of the Lawrence Berkeley Laboratory* (University of California Press, Berkeley, CA, 1989), pp. 317–352.
29 Unlike the claims of his biographers, Rutherford's design indicates that he intended to use the quartz for measurement on hydrophones, and only later did he consider producing ultrasonic waves. This is also suggested by the fact that the BIR annual report of 1916 refers to Rutherford's notice as that on a 'method of measuring vibrations of diaphragms by the quartz "piezo-electrique"' (p. 19).
30 Especially NB 19, Rutherford–Bragg and Rutherford–Boyle correspondences.
31 NB 19 does not mention how the quartz was connected to the diaphragm. The above description is based on Rutherford's calculations for the effect of crystal on the diaphragms, on the description in Rutherford's note and on Boyle's report to Rutherford on his own later experiment in which 'the microphone was mounted on the piezo—in a manner something like what you described' (Boyle to Rutherford, 12 December 1916; see below). The use of a diaphragm whose other side is in air is described in J. H. Powell and J. H. T. Roberts, 'On the frequency of vibration of circular diaphragms', *Proc. Phys. Soc. Lond.* **35**, 170–182 (1923).
32 Rutherford to Bragg, 5 November 1916; similarly 2 November 1916. Rutherford therefore did not explore in these experiments the possibility of ultrasonic echo detection, so it is misleading to quote these sentences in the context of the sonar research as does Campbell, *op. cit.* (note 2), p. 371.
33 Bragg to Rutherford, 8 November 1916; Wood to Rutherford, 10 November 1916.
34 de Broglie to Langevin, 23 December 1918; de Broglie to Rutherford, autumn 1916.
35 Rutherford NB 19, p. 16; Boyle to Rutherford, 12 December 1916; Rutherford to Boyle, 2 December 1916.
36 Boyle to Rutherford, 12 December 1916. Boyle and Smith BIR 28 November 1916.
37 No further experiments with the device are mentioned in Boyle–Rutherford correspondence. For example, the next letter by Boyle, of 2 January 1917, again discusses supersonic transmitters

(not piezoelectric). On 12 January, Boyle asked Rutherford 'what you wish me to do with your quartz piezo-électrique', asked again on 13 February, and on 2 March he verified that Rutherford had received the device.

38 Boyle to Rutherford, 12 January 1917, p. 6.

39 Boyle BIR 9 September 1916 and 23 November 1916 (quote on p. 7). BIR report 31 December 1916, p. 21.

40 Boyle to Rutherford, 5 October 1916, 22 October 1916 and 2 January 1917.

41 Boyle 19 October 1918, p. 2; see also Boyle to Rutherford, 12 January 1917, where he showed ignorance of basic experimental findings from the early 1880s.

42 Boyle 19 October 1918, pp. 2–3. Indeed, also in his first report on Langevin's work Boyle did not see any similarity to Rutherford's device, which he did not mention at all (Boyle BIR 1 August 1917).

43 Yet even Hackmann seems to follow Boyle's explanation: *op. cit.* (note 4), pp. 80–85.

44 Boyle and Smith BIR 28 November 1916, pp. 2–3.

45 In a letter to Rutherford from 2 March 1917, Boyle mentioned 'amplifying by valve after valve', a practice common with the French valves, as a result of their lower amplifying power. Wood's comparison of valves after the war (BIR 12 December 1918) shows that their properties were very similar. Most of these characteristics were already shared by 1916 models (but not by earlier models in Britain): Gerald F. G. Tyne, *Saga of the vacuum tube* (Prompt Publications, 1977), pp. 200–232.

46 BIR 31 December 1916.

47 G. W. White designed soft valves in Cambridge from autumn 1914: Tyne, *op. cit.* (note 45); also Keith R. Thrower, *History of the British radio valve to 1940* (M.M.A. International, Ropley, Hants., 1992), pp. 32–35.

48 Boyle to Rutherford, 17 April 1917.

49 Langevin, *op. cit.* (note 14), p. 47.

50 For this claim see, for example, Hackmann, *op. cit.* (note 4), p. 80. Langevin, however, explains that a special crystal was needed for his later work on the transmitter. In the latter case it is important that the crystal would vibrate near resonance, but this is not a perquisite for a receiver. *Ibid.* (French version), pp. 10–11.

51 *Ibid.*; see also Paul Langevin, 'The employment of ultra-sonic waves for echo sounding', *Hydrogr. Rev.* **2**, 51–91 (1924). Boyle BIR 1 August 1917.

52 Paul Langevin, 'Pierre Curie', *Rev. Mois* **2**. 5–36 (1906); Katzir, *op. cit.* (note 22), pp. 95 and 132; Curie's notebook in Bibliothèque nationale de France—NAF 18369.

53 Bernadette Bensaude-Vincent, *Langevin, 1872–1946: science et vigilance* (Belin, Paris, 1987).

54 De Broglie informed Langevin about Rutherford before February 1917: de Broglie to Langevin, 23 December 1918; Langevin to de Broglie, 27 December 1918; Langevin, *op. cit.* (note 14), p. 27.

55 This restrictive role of the individual instrument resembles the power of *Drosophila* as an experimental system in directing research to questions of chromosomal mechanism to which it was designed, and at the same time discouraging the study of other questions such as those of development and evolution. Kohler describes how, during the 1910s and 1920s, the advantages of the system in the study of genetics directed experimentalists to work on that subject, and diverted them from other kinds of question, not out of any lack of interest but because of the difficulties in applying their experimental system to these issues. Robert E. Kohler, *Lords of the fly: Drosophila genetics and the experimental life* (Chicago University Press, 1994), pp. 173–207.