Petr Nikolaevich Lebedev and his school (On the 120th anniversary of the year of his birth)

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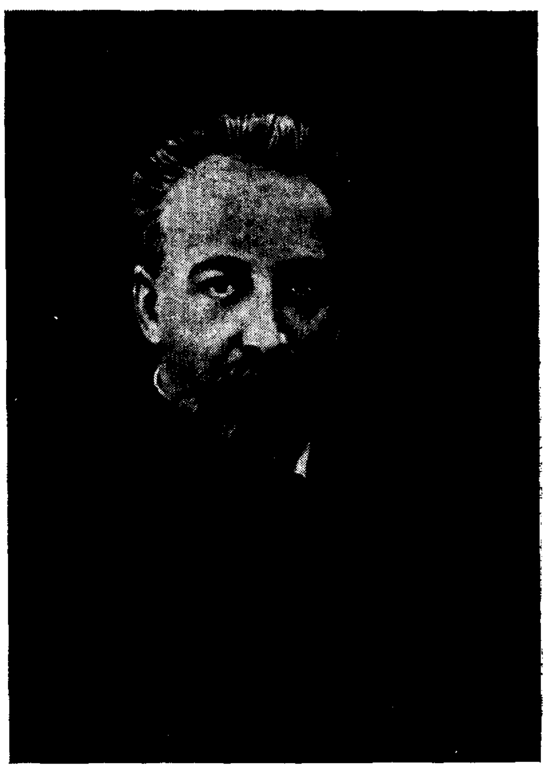
P. N. Lebedev is characterized as a scientist and a teacher. Results of his fundamental investigations in the fields of electromagnetic waves, light pressure, ultrasonics are described. P. N. Lebedev was the first to demonstrate experimentally the pressure of light on solids (1899–1901) and on gases (1907–1909). He developed new methods of generating and detecting millimeter electromagnetic waves and having obtained wavelengths of about 3 mm he laid the foundations of molecular ultrasonics. He is shown to have been a teacher of creative young people and a scientific leader who organized, in Moscow, the first school of physicists in our country. The principal results of the research by P. N. Lebedev's students during the time they worked with him are described.

The outstanding Russian scientist Petr Nikolaevich Lebedev was known in the wider scientific community not only as a distinguished experimental physicist, but also as the founder of the first indigenous school of physics, which he created at Moscow University where he had worked in the physics laboratory from 1891 and as a professor from 1900 onwards. "In addition to winning renown for Russian science with his outstanding investigations of the most pressing scientific problems of his time," wrote his student, T. P. Kravets, "Petr Nikolaevich Lebedev created an extensive physics school in which he nurtured a constellation of talented youth. He was the first to organize a laboratory in which a future physicist could work creatively. The education of a worthy new generation, the preparation of the leading cadres of Russian physics came to be realized on a great scale, without foreign assistance" (Ref. 1, p. 391). The importance of P. N. Lebedev as the educator of creative students was noted by another of his students, N. A. Kaptsov: "A scientist of genius, whose investigations combined exceptional depth of thought with incredible experimental skill, he was simultaneously the organizer of a great collective research effort in physics. He was one of those scientists who are not content to advance science personally, but also involve the younger generation in this quest. Petr Nikolaevich's fondest hope was to convey to his students his method, his ability to think creatively and scientifically, and to educate scientists capable of meeting the needs of the motherland. This he pursued with the same enthusiasm and passion as his own scientific investigations" (Ref. 1, p. 406). Lebedev's closest student and laboratory assistant P. P. Lazarev also spoke of him as "the founder of the first Russian school of physics" (Ref. 2, p. 405).

P. N. Lebedev was born in Moscow on March 8, 1866. Already in his youth he exhibited an aptitude for construction, put together various electric machines and experimented with them, read books on physics and electrical engineering. As a result, at 16 he already developed an interest in studying physical phenomena and decided to become a researcher. In 1884 P. N. Lebedev enrolled in the Moscow Higher Technical School, where he performed his first scientific experiments. Although these did not lead to positive results, they nevertheless built up his experimental skill and taught him mechanics. He did not graduate, however, travelling instead to Strasbourg University, where he became a student of the noted physicist and marvellous pedagogue, A. Kundt. It was precisely at Kundt's Physics Institute that P.



P. N. Lebedev (1866–1912)

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N. Lebedev developed as an experimental physicist: there, in a deeply scientific atmosphere, he laid out his future research plans in physics. In an essay Lebedev vividly depicted A. Kundt's influence, describing how his mentor taught him to "think and work physically" (Ref. 3, pp. 240–263).

At Strasbourg P. N. Lebedev became interested in the nature of molecular forces and structure of matter, and also in Maxwell's electromagnetic theory of light. His first investigations, performed there, studied the electric properties of molecules and the repulsive action of radiating bodies. From this latter work sprang a series of investigations that eventually led to his famous experimental demonstration of pressure exerted by light on solid bodies and gases.

In 1891 P. N. Lebedev received a Doctor of Philosophy degree from Strasbourg University for his study "On the measurement of dielectric constants of vapors and on the Clausius-Mossotti theory of dielectrics." (Ref. 3, pp. 3–26). That same year he returned to Moscow University, full of plans and ideas, and became a supernumerary laboratory technician in A. G. Stoletov's physics laboratory, founded in 1873 and directed at the time by A. P. Sokolov. In the cramped accomodations of Stoletov's laboratory, ill-suited for scientific work, P. N. Lebedev embarked on physical experiments, combined pedagogical activity with a program of pure research whose major goal was to establish experimentally the pressure of light. There he also housed a machine shop for building the essential experimental apparatus. "P. N. Lebedev's masterful and profound investigations were carried out in that ill-equipped laboratory at Moscow University," noted his student V. K. Arkad'ev (Ref. 4, p. 94).

It should be remarked that Lebedev's interest in the microscopic structure of matter permeated all his investigations, beginning with the first: his dissertation, in which he not only experimentally established the validity of Clausius-Mossotti theory, but also furnished new arguments in favor of atomic-molecular structure of matter by approaching molecules as conducting particles capable of reacting to electromagnetic oscillations and resonating with incident electromagnetic waves.

It is impossible to omit Lebedev's second study, "On the repulsive force of radiating bodies," (Ref. 3, pp. 27–32), which proved seminal to the success of his research into light pressure and, in the words of T. P. Kravets, "laid the foundation for the worldwide fame of young Lebedev and for the attention attracted by all his subsequent publications" (Ref. 5, p. 18). Lebedev first reported on this piece of research at F. Kohlrausch's seminar at Strasbourg in June of 1981.

"The purpose of this paper," wrote P. N. Lebedev, "is to demonstrate to what fraction of Newtonian attraction corresponds the repulsive light radiation, both for the Sun and for any other spherical body that is not at absolute zero" (Ref. 3, pp. 27–28). He ended the paper with the conclusion that "in studying the nature of so-called 'molecular forces' we cannot neglect forces due to radiation without first determining their contribution to the total molecular force and separating this known force from the unknown others" (Ref. 3, p. 92).

In that paper P. N. Lebedev also concluded that the shape of a comet's tail is determined by the mechanical action of solar rays. Whereas J. Kepler suggested a similar idea as a brilliant but intuitive guess, P. N. Lebedev's assertion was theoretically well-founded, for he was convinced that light exerted pressure on the gaseous molecules of the comet—this conviction was based on a deep understanding of molecular forces and Maxwell's theory of mechanical pressure exerted by light on matter. He also established theoretically that the pressure exerted by the Sun's rays on small particles in outer space may prevail over attractive Newtonian gravitation, and that this effect would become more pronounced in spherical cosmic particles of smaller radius. After the report of the results of this work, F. Kohlrausch concluded the seminar by saying: "I consider all this a very promising idea. However these conclusions must be advanced with great care and, above all, supported experimentally" (Ref. 6, p. 564). P. N. Lebedev was of the same opinion and embarked on an active realization of his plans in Stoletov's laboratory.

In 1894–1897 he carried out a cycle of studies into the effect of electromagnetic, hydrodynamic, and acoustic waves on resonators. His results were first published as separate papers and then, in 1899, came out in a separate edition "An experimental investigation of the ponderomotive action of waves on resonators" (Ref. 3, pp. 56–120). Here Lebedev established that all waves have a mechanical effect on a resonator, regardless of their nature. He also discovered several regularities pertaining to this effect. "The completely identical effect of ponderomotive forces observed experimentally for such different oscillatory motions as electromagnetic, hydrodynamic, and acoustic oscillations," wrote Lebedev, "establishes that the underlying laws responsible for the observed phenomena must be independent of the physical nature of the oscillations and the resonators subjected to them. In this case the regions of validity of the observed laws should be widened considerably. In principle, the main purpose of studying the ponderomotive effect of oscillatory motions lies in the possibility of extending its laws to the area of light and thermal radiation due to individual molecules and thus predicting the nature and magnitude of intermolecular forces" (Ref. 3, pp. 119–120). For this research P. N. Lebedev was awarded (in 1899) the degree of Doctor of Physical-Mathematical Sciences without the customary magisterial dissertation.

In the course of the above cycle of experiments Lebedev also obtained important results in the field of electromagnetic oscillations, which made him a pioneer in the physics of millimeter electromagnetic waves. He developed new methods of generating and detecting millimeter electromagnetic waves. Using his 26-centimeter vibrator H. Hertz obtained 60 cm waves, whereas Lebedev obtained twenty-fold shorter wavelengths with his personally designed miniature vibrator. His high-sensitivity thermoelectric detector was equally effective. Having such instruments at his disposal Lebedev generated 6 mm and even 3 mm electromagnetic waves. "... observed weak but unmistakable signs of oscillations at $\lambda = 3$ mm," wrote P. N. Lebedev. "To date these are the shortest electromagnetic waves ever observed in the spark discharge of conductors." (Ref. 1, p. 222). This Lebedev record was surpassed only in 1922 by A. A. Glagol'eva-Arkad'eva, a student of V. K. Arkad'ev. Experimenting with 6 mm waves Lebedev observed the same effects as H. Hertz: reflection, refraction, polarization, and interference, also discovering (in 1895) a new effect—double refraction in crystals (Ref. 1, pp. 127–141). This was yet another confirmation of Maxwell's theory that light and electromagnetic waves are manifestations of the same phenomenon.

It should be noted that Lebedev developed his methods of generating and measuring electromagnetic waves in a new spectral range on the basis of optical methods. H. Rubens and P. N. Lebedev, "traveling" towards each other along the electromagnetic spectrum, tried to close the gap between the longest infrared waves and the shortest Hertz waves. The former obtained record infrared rays at $\lambda = 0.3$ mm; the latter generated electromagnetic waves of $\lambda = 3$ mm.

Already in those distant years P. N. Lebedev clearly recognized that physics cannot be content with the range of electromagnetic waves that had been achieved, and that yet shorter wavelengths were necessary to study the structure and properties of matter. "...Having reached waves with $\lambda = 1$ mm we enter a new wavelength regime corresponding to molecular oscillations of matter," he wrote. "But for an exhaustive investigation of the properties of matter we need oscillations that are shorter still. Thermal radiation ... cannot yield waves of $\lambda > 0.1$ mm; we need to develop a new generator for waves between $\lambda = 3$ mm and $\lambda = 0.1$ mm ... a method of generating even shorter wavelengths will be a great advance in the area of experimental physics" (Ref. 1, pp. 222–223). These insights of our great compatriot contributed to the prehistory of millimeter and submilliter spectroscopy, which came to the fore in the 20th century, in the 1940's.

In a way P. N. Lebedev's studies of electromagnetic waves were a prelude to his subsequent, seminal investigations devoted to measuring light pressure. They sharpened his experimental skills and reinforced his confidence in the success of newer, more difficult and subtle experiments. It was in the course of these studies, as well as his acoustics research, that P. N. Lebedev found his first students: P. B. Leĭberg, V. A. Al'tberg, V. D. Zernov, N. P. Neklepaev, N. A. Kaptsov, T. P. Kravets, A. R. Kolli, and V. I. Romanov.

The students worked on problems suggested by P. N. Lebedev. Thus, P. B. Leĭberg studied the damping of acoustical resonators, following up Lebedev's own research into the ponderamotive effect of acoustical waves on resonators (1896),[7] A. R. Kolli researched the dispersion of electromagnetic waves in liquids (1899),[5] T. P. Kravets studied the dielectric permittivity of water in a high-frequency field. The latter two subjects were closely connected to Lebedev's paper "On the double refraction of rays of electric force" (1895).

In this fashion P. N. Lebedev laid the foundation not only of collective experimental physics in Russia, but also of his own school of physics. "It is difficult to say what was dearer to Petr Nikolaevich, his own research or the research of his students," remembered N. A. Kaptsov. "Petr Nikolaevich's fondest dream was to pass on to the students his enormous experimental experience and his ability to think creatively about physics, to educate scientists who would advance physics and satisfying the technical and economic needs of the country... . The appeal of this bright spirit was immeasurably great: he was not only a scientist of genius who combined profound scientific thought with extraordinary experimental skill, but also the leader of a physics school who dearly loved his students. Not only did he advance science like no other, but he did everything in his power to attract a new generation to science, to find successors who would carry on his work" (Ref. 9, p. 328).

In 1899 P. N. Lebedev embarked on the experimental confirmation and measurement of light pressure, a qualitatively new stage in his scientific work. As is well known, J. Kepler was the first to predict the phenomenon of light pressure in his treatise *DeHarmonice Mundi* (1619) in order to explain the bending of the comets' tails away from the Sun. L. Euler also wrote about the mechanical effect of light on matter in 1746. Theoretically light pressure was implicit in Maxwell's theory, and he was the first to compute its value (1873). A different approach was pursued by A. Bartoli, who also computed the value of light pressure from thermodynamical principles in 1876. In the 19th century many scientists attempted to prove the existence of light pressure: A. Fresnel (1825), W. Crookes (1874), F. Zöllner (1877), A. Righi (1877), F. Paschen, A. Bartoli (1874), and earlier still G. de Meran and C. Dufay (1754) who carried out the first experiments. But all these efforts ended in failure, although Crookes' experiments discovered other, so-called radiometric forces which, it was later realized, together with the convection act to mask the true light pressure.

To carry out a fundamentally new cycle of experiments involved enormous experimental difficulties which had previously defeated even such masters of experiment as W. Crookes, A. Righi, and F. Paschen. Persistence and ingenious new solutions were necessary for success. Indeed, the pressure exerted by light on matter is extremely small and is further masked by the stronger radiometric and convective forces. P. N. Lebedev reduced these forces considerably by placing his apparatus in the best vacuum possible in those days, achieved by evacuating the remaining gaseous particles from the vessel with mercury vapors that were subsequently frozen out (here we find the mercury diffusion pump in its original form). Overcoming enormous experimental difficulties Lebedev directly demonstrated the pressure exerted by light on matter. In 1900, at the World Congress of Physicists in Paris, P. N. Lebedev made a preliminary report on his experiments (Ref. 1, pp. 184–185) (Lebedev had reported the results of his preliminary experiments on May 17, 1899 at a meeting of naturalists in Lausanne (Ref. 1, pp. 190 and 423–424)). He completed the experiments in the beginning of 1901. In a detailed paper "An experimental investigation of light pressure" (Ref. 1, pp. 187–210) published in 1901, Lebedev wrote: The results obtained may be summarized as follows:

1) the incident light beam exerts pressure on both absorbing and reflecting surfaces; and these ponderomotive

forces are not due to the secondary radiometric and convective effects that are caused by heating;

2) the force of light pressure is directly proportional to the energy of the incident light and is independent of color;

3) within experimental error ($\pm 20\%$ was Lebedev's own estimate of his experimental error—*Yu. Kh.*) the observed light pressures equal Maxwell-Bartoli's values for the pressure of radiant energy. Thus, in the case of light beams the existence of Maxwell-Bartoli forces has been demonstrated experimentally" (Ref. 1, p. 210).

P. N. Lebedev's experimental research brought him world renown and promoted him to the rank of outstanding experimental physicists of the day. "In all its details P. N. Lebedev's work will remain a shining example of experimental skill, persistence, and ability to overcome the difficulties engendered by imperfect technology," wrote T. P. Kravets. "This paper enjoyed great and well-deserved success in the scientific community. Major journals in all languages reprinted it in its entirety or summarized it" (Ref. 10, p. 311). For his part, the noted English physicist W. Thomson (Lord Kelvin) remarked: "... . All my life I argued against Maxwell and refused to accept his theory of light pressure, and now ... Lebedev forces me to concede with his experiments" (Ref. 2, p. 415). F. Paschen also held a high opinion of the results obtained. "I consider your result one of the greatest physical successes of the recent years; I do not know by what I should be more impressed—your experimental skill and artistry, or the theory of Maxwell-Bartoli," he wrote. "I appreciate the complexity of your experiments the more, as some time ago I myself attempted to demonstrate light pressure and carried out similar experiments, which however did not yield a positive result as I could not manage to suppress radiometric effects" (Ref. 6, p. 569).

With the same energy and clarity of purpose P. N. Lebedev embarked on a final series of experiments to demonstrate and measure the pressure exerted by light on gases, a supremely difficult problem.

P. P. Lazarev wrote this on the skill and persistence P. N. Lebedev exhibited in these investigations: "It is impossible to list all the variants of the experiment that were tried; suffice it to say that completed pieces of apparatus—the instruments used to carry out the measurements—numbered up to twenty. Many times it appeared that the experiment yielded a completely negative result, that all the secondary perturbing forces could not be excluded, that the effect could not be observed, and every time Lebedev hit upon a hunch which led to a new experimental variant and, in the end, brought the brilliantly conceived investigation to a satisfactory conclusion" (Ref. 3, pp. xviii-xix).

In 1909 P. N. Lebedev finally and unequivocally demonstrated the existence of light pressure on gases (Ref. 1, pp. 299-321; Ref. 12, p. 141) (the preliminary report (Ref. 1, pp. 280–281) came out in December of 1907). "Long concentration, brilliant experimental technique, and a subtle understanding of the mechanics of the phenomenon allowed him to complete the work successfully and to substantiate the major assumption," noted T. P. Kravets in this regard. "This investigation stands as an unsurpassed and perhaps unmatched example of experimental artistry. Nobody attempted to duplicate it. Having completed it, P. N. Lebedev could rightfully say that he formulated and solved one by one all the problems clustered around the light pressure predicted by Maxwell" (Ref. 10, p. 313).

As we have seen, this student of A. Kundt and the greatest exponent of his school of experimental physics garnered the fame of a virtuoso experimenter in his own right, carrying out investigations that astound by their brilliance and deep intuition despite the modest means available at the limit of technical possibilities of his day.

The demonstration of pressure exerted by light on solids and gases was of paramount importance to physics in general and to the ultimate success of Maxwell's theory of the electromagnetic field in particular. An additional result of Lebedev's experiments was the fact that light possessed momentum as well as energy—a fundamental conclusion in its own right. It suffices to consider Lebedev's expression for light pressure $P=(E/c)(1+\beta)$, where E is the radiant energy incident on the absorbing surface, c is the speed of light, β is the reflection coefficient of the surface (taking light pressure to be numerically equivalent to the momentum change mc), to "bridge" the gap towards the Einsteinian equivalence of mass and energy $E=mc^2$.

"... The demonstration of light pressure made the inseparable link between mass and energy, later fully exposed by the theory of relativity, incomparably easier to formulate," wrote S. I. Vavilov in this regard. "The elementary light pressure in modern quantum physics—the momentum of a photon $h\nu/c$—is a generalization of Lebedev's result which explained the specifics of x-ray and gamma-ray scattering. The so-called Compton effect is, in fact, Lebedev's experiment extended to the quantum process of a photon colliding with an electron. Thus Lebedev's research into light pressure was not an isolated episode, but an experimental hub of the greatest importance which determined the development of relativity, quantum theory, and modern astrophysics. ... The experimental physicist, as well as the historian, will turn to P. N. Lebedev's research as a primary source for a long time to come" (Ref. 11, p. 96).

P. N. Lebedev's studies of light pressure were the high point of his scientific career. In that same period he began actively to build a school of experimental physics. He understood perfectly and was the first in Russia to demonstrate that the collective approach to scientific research was the most fruitful. The subject of light pressure appeared in the works of Lebedev's students as well. It is noteworthy that the research of all his students was intimately connected with his own, often extending his work—in other words, links in the same experimental chain. "How varied and yet how connected are the areas of the students' research," wrote V. D. Zernov in this regard. "This unity of ideas bound the students into a tight, cooperative group; the common thread of ideas running between the work of the teacher and his students linked them together" (Ref. 12, p. 145).

In the same vein T. P. Kravets wrote: "... They (the students—*Yu, Kh.*) always knew that their efforts were not disparate or random, that the bricks they brought and laid under the eye of the master architect built up a magnificent edifice marked by pure and classical lines" (Ref. 13, p. 288).

Proceeding by analogy from the existence of light pressure P. N. Lebedev suggested that any wave-like process should exert pressure on matter. The proof of this assumption he left to his students. Thus in 1901 V. Ya. Al'tberg measured the pressure of sound waves,[14] and in 1902 N. A. Kaptsov did the same for surface water waves.[15] Later V. D. Zernov constructed an instrument based on Al'tberg's sound pressure method to measure the intensity of sound in absolute units.[16]

The aforesaid studies of Lebedev and his first students were carried out after hours in Stoletov's physics laboratory for students. Lebedev "found" his students among those engaged in applied physics exercises.

Of greatest importance in the education and schooling of his students were P. N. Lebedev's weekly colloquia, modelled on those of Kundt, which Lebedev was the first in Russia to organize at a physics laboratory in 1901. These Wednesday colloquia served as a kind of higher school. "... The impact of Lebedev's colloquia," remembered P. P. Lazarev, "was absolutely incredible in addition to enormous insight he had the astonishing ability to make things clear to a beginner. From the start I was astounded by Lebedev's patience when listening to young physicists who occasionally defended an obviously untenable point of view. This feature undoubtedly served to gain the sympathies of younger people. A large group of beginning physicists gathered around Lebedev and later very able scientists came from their ranks .... I had the opportunity to attend a course given by Lebedev for those working in his laboratory. The course was devoted to the current breakthroughs in physics—Lebedev lectured with outstanding flair and captured the student audience completely .... Lebedev's special lectures demonstrated his enormous erudition not only in his own field, but in fields far removed from his work .... Gradually these colloquia came to be one of the constant, integral parts of Lebedev's university teaching" (Ref. 17, p. 574). And, later on: "Everyone attending these colloquia, from the beginning student to the leader himself, felt a member of a big family, thus forming the working collective so indispensable in scientific research" (Ref. 2, pp. 419–420).

T. P. Kravets was equally excited about Lebedev's colloquia. "There is no stronger memory in our lives than these unforgettable colloquia," he writes, "where some of us students grew into young but already independent scientists to whom our teacher appeared in a new, even more brilliant light. Only here P. N.'s colossal erudition, brilliant inventiveness, aptness of scientific definitions, and wealth of reminiscences reached us with full force" (Ref. 10, p. 310).

Thus, in straitened circumstances, P. N. Lebedev not only carried out fruitful scientific work of original and fundamental character, but he also educated the next generation of physicists. "He demonstrated by his research," wrote T. P. Kravets, "that even in the difficult conditions of the 1884 University Edict and pre-revolutionary political atmosphere it was possible to create an indigenous, Russian scientific research center—and no second-rate institution at that, but one that attracted the attention of the worldwide scientific community. He showed the youngsters what kind of work it took to become a true scientist, and what it meant to be a true scientist. He put the labors of creativity and research above those of learning by rote. In his laboratory individual university attendees' (as students were defined in the aforementioned University Edict) coalesced into a single, working collective pursuing one plan, reaching for the same goal..." (Ref. 16, p. 103).

The construction of the Physical Institute at the Moscow University was completed in 1904. Lebedev's own laboratory received two large rooms on the second floor and additional semi-basement room—"Lebedev's basement"—for Lebedev-directed research. This permitted him to widen the scope of research. Hence only in 1904 did Lebedev receive a true laboratory for scientific research with its own machine shop, rather than one for student exercises. This laboratory became a center of attraction for creative young scholars: if in 1896 Lebedev only had three co-workers, and ten in 1900, by 1911 he had 28. Thus, by 1905 about ten different topics were pursued by young physicists in the laboratory. Already by 1910 the laboratory had 1229 instruments on hand, many of them manufactured by the researchers themselves, and a large series of experiments based on Lebedev's ideas was in progress.

At this point the research was mainly focussed in two directions: acoustical physics and physics of electromagnetic oscillations. Together with V. Ya. Al'tberg, V. D. Zernov, and N. P. Neklepaev, Lebedev carried out pioneering research into the generation, transmission, and reception of ultrasound waves in air. In particular, in 1906 he proposed the generation of ultrasound by spark discharge. He was the first to obtain a wide range of ultrasound oscillations, up to 400 kHz, and to analyze them spectrally. With his students Lebedev constructed a number of ultrasound detectors, employed to obtain quantitative data on the pondermotive forces of an ultrasound field (V. Ya. Al'tberg, 1903). In addition, in 1907 Al'tberg obtained acoustical waves with $\lambda = 1$ mm.[20] In 1911 Neklepaev studied the absorption of ultrasound in air, established its anomalous absorption, and obtained the cutoff wavelength of a sound wave in air. Using a method suggested by Lebedev he measured the absorption coefficients of acoustical waves in the 2.5–0.8 mm range.[21] The experimental data obtained did not agree with the existing hydrodynamic theory of Stokes-Kirchhoff. Having analyzed the absorption of ultrasound in air, Lebedev concluded that acoustical waves of very short wavelength cannot be produced because of their absorption by gases in which they travel. He suggested that this was due to the viscosity and thermal conductivity of gases and proposed a possible mechanism for absorption and dispersion of ultrasound in gas. These fundamental studies of ultrasound by Lebedev and his students gave birth to the field of molecular ultraacoustics, preceeding analogous foreign research by some 20 years.

Another series of experiments carried out by Lebedev and his students concerned electromagnetic oscillations, extending as it were his own 1893–1895 research in the field. Thus, V. I. Romanov studied the absorption of electromagnetic waves,[22] N. K. Shchodro studied undamped oscillations,[23] V. K. Arkad'ev investigated the magnetic properties of matter in varying high-frequency fields,[24] K. P. Yakovlev developed an infrared spectrometer that made it possible to determine automatically the absorption at various frequencies.[25] In addition, A. K. Timiryazev investigated internal friction in gases,[26] P. P. Lazarev studied the temperature discontinuity at the interface between a solid and a gas,[27] and so forth.

P. N. Lebedev considered the research carried out in his laboratory to be his life's work and followed it with great love and attention. "The laboratory was his element, the tight group of people sharing his scientific interests," T. P. Kravets remembers. "Here he loved to talk at length, hours at a time, and here his inspired discussion was rich in imagery and insight; the concepts he employed to flesh out his scientific ideas were insistently simple, even anthropomorphic, whereas his ideas were constantly full of unexpected analogies and paradoxes. The students will long remember his apt and figurative remarks. Discussions in the laboratory—they were among the students' most vivid memories. No doubt they were one of the main reasons that attracted people to working with him..." (Ref. 13, p. 290).

The laboratory followed a definite plan and a program composed by Lebedev himself. Before suggesting research subjects to his students, Lebedev would rigorously think the problem through several times: there was always a definite goal and a clear method of attacking the central question. Rather than simply experiment and hope for good fortune, Lebedev would consider all the details of the proposed investigation. The majority of the problems proposed to his students had been included in Lebedev's research journal long before the experiments were actually attempted. Every day Lebedev would inspect the laboratory rooms in the "basement", talking to each worker in turn, often at length—and he never treated the novice student attempting his first experiment differently from the experienced worker, demanding a clear report on the work in progress from all.

K. A. Timiryazev characterized the laboratory activity of that period thus: "... In the "Lebedev basement"... beats the pulse of real, not pedagogical science ... one that does not rest on the achievements of years and centuries long gone, but one in tune with modern science and future technology. Here Lebedev finds the time to supervise the work of 20–25 young researchers, contributing to their efforts an excess of his own creativity, his own amazing inventiveness" (Ref. 28, p. 64).

Educating future scientists P. N. Lebedev followed the advice and methods of his teacher, A. Kundt. N. A. Kaptsov writes: "Petr Nikolaevich Lebedev taught the beginning physicists working under him to work "physically", he helped them to learn all the subtleties of experimental skill, he taught them to think through physical problems rigorously, to express their ideas on paper, to plan their work. He inculcated in them that a scientist is obligated to do scientific research. He inspired many of them for the rest of their lives by his outstanding talent and great personal appeal, directing their work along a definite course in some branch of physics" (see Ref. 1, p. 411).

N. A. Kaptsov also describes how Lebedev achieved all this: "First of all, Petr. Nikolaevich required that everyone working in the laboratory clearly thought through the plan of his research. But this research plan had to be active and malleable, rather than ossified and set in stone. As soon as some new effect appeared in the course of research, Petr Nikolaevich would ponder it briefly and then, with new enthusiasm, suggest a different, unexpected direction. He would immediately come up with a multitude of new ideas. He would get caught up in these ideas, sketch bright new vistas to the young researcher infect him with enthusiasm. In these minutes, perhaps more than at any other time, we would pass on to his students a portion of that invaluable skill of—in Kundt's words—"thinking physically", and initiate them into his scientific creativity" (Ref. 1, p. 409).

Lebedev's criticisms and instructions were never in the abstract. When he explained how to write a paper we would outline its structure, sketch the figures, etc. He did not permit a colloquim report or submitting a paper for publication if he thought the research unfinished, or the paper in need of stylistic reworking. Lebedev tried to teach his students to write clearly and sparely, forced them to rework the text several times, to consult other sources. He valued highly self-motivated education and the broadening of the mental horizon, telling his students: "Read everything, perhaps you will not understand it all at once, but the time will come and you will digest what is required for your research. Do not try to appear in the laboratory too often—read more, think and plan: devise new experiments and investigations" (Ref. 4, p. 95).

Approaching each worker individually, Lebedev captivated his students by his range of ideas. "... By his ceaseless, sharp, and determined propagandizing he ultimately reached the stage when a small group of young scientists formed around him: thinking in the same way, working on the same problems, and striving for the same conditions as their teacher," wrote T. P. Kravets (Ref. 10, p. 318).

As a result, on the foundation of his physics laboratory he built a school of experimental physics, the origins of which date back as far as 1893. "A great scientist and teacher himself, he wanted to investigate the properties of phenomena that attracted his interest and to find practical applications for these phenomena, and so he attracted students—generously dispensing his ideas," wrote V. D. Zernov. "He knew how to bring out what lay buried within us, he was able to implant in us a love of science and an enthusiasm that lasted a lifetime, which we now pass on to our students inasmuch as our means and abilities permit" (Ref. 12, p. 143). Already in 1893 P. N. Lebedev wrote in his diary: "A wealth of ideas and projects leaves me no quiet time for work" (Ref. 2, p. 418). It stands to reason that he tried to involve his students in his ideas.

Lebedev's school was the first indigenous school of physics in the modern meaning of the word: with its own style characterized by exact formulation of problems, high demands on experimental technique, and profound scientific scrupulousness; with its own program, spirit of cooperation, and a true scientific atmosphere. By 1911 the school reached its peak, but in that year, because of the reactionary policies of the Tsar's Minister of Education, L. A. Kasso, Lebedev and other progressive faculty were compelled to leave Moscow University. He was much pained by leaving the university and his own laboratory, the fruit of so much labor, for it spelled the end of his plans and his scientific activity.

By leaving the university P. N. Lebedev once again demonstrated his high social conscience: it was an act of enormous courage accompanied by great emotional suffering that fully exhibited his decisive character and unfailing solidarity with his colleagues.

In the letters to the Editor column of the March issue of *Russkie Vedomosti* ("The Russian Record", a pre-revolutionary monthly) Lebedev's students tried to attract public attention to the first Russian school of physics and to its role in the development of natural sciences in Russia. "In the brief time he could work in Moscow unfettered," they wrote about Lebedev, "he managed to build an extensive scientific school. His laboratory leads almost all others in the world in the number of actively pursued research projects, out of all proportion to its small size and the modest means available to run it. Recently up to 30 research projects were carried out simultaneously, within a unified framework. It was by the combined efforts of the Moscow school that several questions in physics were fully and exhaustively answered.

"The fruits of this activity are plain to see: in the short existence of the laboratory 5 doctoral and magisterial dissertations and over thirty other scientific papers were turned out. Two faculty chairs are occupied by the laboratory's former students, and it has furnished several dozen laboratory technicians, assistants, lecturers, and professors at institutions of higher learning both in Moscow and at universities elsewhere."[29]

Under extremely difficult conditions a new, privately financed physics laboratory was organized at the A. Shanyavsky Moscow Municipal University in the basement of an apartment building on the Mertvyĭ Lane (now Ostrovsky Lane). Lebedev transferred his operations and students there, preserving the scientific school. There he also carried out his last piece of research, on the magnetism of rotating bodies. He also resurrected his famous colloquia under the auspices of the Moscow Physical Society, significantly broadening their audience. But a hereditary heart condition, enormous stress and, finally, the suffering caused by recent events took their toll—on March 1, 1912 Lebedev passed away.

In a letter of condolences to V. A. Lebedeva dated May 1, 1912, H.-A. Lorentz wrote: "I considered him one of the first and finest physicists of our time and admired the way he managed during the past year to preserve the Moscow school which he founded and to continue his research in such unfavorable conditions... May his spirit live on in his students and colleagues, and may the seeds he had sown bring a full harvest!" (Ref. 6, p. 606).

And truly, the seeds had been sown and the harvest was full. Lebedev's school continued its existence under the direction of P. P. Lazarev. Another bequest of Lebedev's, who had always persuaded his students to continue attracting creative young people to science, came to pass: not long before Lebedev's death S. I. Vavilov, S. N. Rzhevkin, T. K. Molodyĭ and others joined the school, and although they did not benefit from constant contact with Lebedev, they had almost directly imbued the traditions and style of the school from their older student colleages.

In addition to the results described above, Lebedev's students obtained a number of fundamental results, markedly extending and broadening Lebedev's scientific directions and taking on new ones. Lebedev's school turned out two academicians and three corresponding members of the Academy of Sciences of the USSR, more than ten doctors of science and professors; P. P. Lazarev, N. N. Andreev, V. K. Arkad'ev, N. A. Kaptsov, and T. P. Kravets went on to found their own scientific schools.

Lebedev's school has already produced several generations of scientists—and therein lies its vitality. And if in our day a full range of physical science covering all fields flourishes in our country, and numerous schools of physics carry on research, to some extent the roots of these achievements lead to P. N. Lebedev—the great scientist and teacher, citizen and patriot, "whose ideas and undertakings," wrote S. I. Vavilov, "could only be realized in Soviet Russia" (Ref. 30, p. 248). It is no accident that, as a tribute to the great Russian physicist, the Physics Institute of the Academy of Sciences of the USSR bears his name, and the Presidium of the Academy of Sciences of the USSR awards a P. N. Lebedev prize to Soviet scientists for outstanding contributions in the field of physics. On the 120th anniversary of the year of his birth Soviet physicists pay tribute of great gratitude and respectful memory to the man who by his works brought acclaim to Russian science and made an enormous contribution to the education of creative young people.

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