Lev Vasil'evich Shubnikov (on his eightieth birthday)[2)]

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Lev Vasil'evich Shubnikov is the founding father of Soviet low-temperature physics. The development of this field with his active participation began in the Soviet Union in the early thirties.

Lev Vasil'evich Shubnikov was born on September 29, 1901. In 1926, he graduated from the Leningrad Polytechnic Institute. During his student years (1920–1922), he worked as a laboratory assistant to I. V. Obreimov at the State Optical Institute. Subsequently, Shubnikov moved to the Leningrad Physico-Technical Institute (LPTI) as an assistant.

To evaluate Shubnikov's role in the development of Soviet physics a brief assessment should be made of low-temperature physics during those years. Subsequent to the discovery of superconductivity by Kamerlingh Onnes in 1911 (and studies of the same interrupted by the first World War), investigations of this effect resumed in the early twenties. All the basic work was conducted at the University of Leiden where Onnes organized and maintained the at the time the only laboratory for low temperatures. At that time, methods for the liquefaction of gases (helium, hydrogen and even air) were still very primitive. Accordingly, amounts of liquefied gases used in experiments were small. In the Soviet Union, cryogenics laboratories were nonexistent at that time.

It is 1926 and, on his having graduated from the Leningrad Polytechnic Institute, Narkompros (the State Commissariat on Education) directs Shubnikov to proceed to the Leiden Laboratory where until 1930 he works under Professor de Haas. At this point it should be mentioned that Shubnikov's activity in the physics of crystals goes back to his student days. Thus, in 1924 he and I. V. Obreimov, for whom Shubnikov worked, developed a method for making metal single crystals from melt, known today as the Obreimov-Shubnikov method. Subsequently, Shubnikov developed an optical method for investigating the elastic and residual deformations in crystals. He and Obreimov used this method successfully in 1926 to study plastic deformation of rock salt and obtained several very interesting results.

LEV VASIL'EVICH SHUBNIKOV 1901-1945

In de Haas's laboratory, Shubnikov was asked to make perfect single crystals of bismuth. These crystals were to be kept at low temperatures to study electrical conductivity in an external magnetic field, and to study the Hall effect. Having earlier experience in the area of physics of crystals, Shubnikov brilliantly tackled this problem.

To make single crystals, Shubnikov followed P. L. Kapitza's method of using a sectional mold. Using as the starting material pure bismuth which he obtained by chemical purification and repeated recrystallization, Shubnikov produced single crystals of unprecedented high quality containing only small amounts of impurities and defects. He used these crystals to study variations in electrical resistance in a magnetic field at low temperatures. In contrast to a smooth variation of the resistance with magnetic field observed earlier, Shubnikov discovered distinct oscillations in the resistance (the Shubnikov-de Haas effect).

Subsequently, using similar perfect single crystals made by Shubnikov, de Haas and van Alfen observed the oscillating variations of magnetic susceptibility, an effect which carries their names. It was found that the resistance oscillations in the Shubnikov-de Haas effect are periodic in the reciprocal of the field. This period is independent of the external field and temperature and it is defined both by metal properties and the orientation of the external magnetic field with respect to the crystallographic axes of a single crystal specimen. The oscillation amplitude decreases with rising temperature.

[1)]This article contains reports presented at the November 18, 1981 scientific session of the Division of General Physics and Astronomy and the Department of Nuclear Physics of the Academy of Sciences of the USSR.

[2)]The following reference materials were used in this article: O. I. Balabekyan, Usp. Fiz. Nauk 89, 321 (1966) [Sov. Phys. Usp. 9, 455 (1966)] and Development of Cryogenics in the Ukraine, Naukova dumka, Kiev, 1978.

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It was shown later that both the Shubnikov–de Haas and de Haas–van Alfen effects are purely quantum effects which arise as the result of the energy levels of conduction electrons undergoing quantization in a magnetic field. The discovery of the Shubnikov–de Haas effect may be viewed as the beginning of the quantum physics of normal metals. This effect, for a long time, could be observed only in bismuth. However, advances in metal purification procedures and the availability of perfect single crystals make it possible today to observe resistance oscillations in a magnetic field in the majority of metals and in many semiconductors. We know that the period of oscillations of the resistance in the reciprocal of the magnetic field is determined by the area of the intersection of the Fermi surface with a plane which is perpendicular to the direction of the external magnetic field $\Delta(1/H) = eh/cS$, where S is the cross sectional area of the Fermi surface. Thus, measurements of resistance oscillations in a magnetic field permit one to determine S and to find the shape of the Fermi surface. By measuring the temperature dependence of the oscillation amplitude, the effective mass of the current carriers m^* may be determined. The Shubnikov–de Haas and de Haas–van Alfen effects are examples of the basic methods for studying the electron properties of metals and semiconductors.

After his return home from Leiden in 1930, Shubnikov moves to the Ukrainian Physico-Technical Institute (UPTI). At that time a cryogenics laboratory was being established there at the initiative of I. V. Obreimov, then UPTI's director. In 1931, Shubnikov becomes the scientific director of this laboratory. In a short period under his direction the technical problems of cryogenics were understood and overcome; devices for the liquefaction of air and hydrogen were set up; production of metallic dewars for liquid air up to 50 l was organized; equipment was built for working with liquid helium; and the first experiments were begun in the range of helium temperatures.

In order to assess correctly the scale of Shubnikov's work it should be mentioned that at that time the physics institutes, for instance the LPTI, were allotted approximately 2 l of liquid air per day per laboratory, where a liquefier yielded less than 5 l of liquid air per hour, and liquid hydrogen and liquid helium were totally unavailable. In 1933, the UPTI hydrogen liquefier was already producing 14 l of liquid hydrogen per hour and liquid air was derived from an industrial installation yielding 25 l/hr. True, liquid helium was at first obtained directly from an experimental unit using the Simon expansion method; not until 1935 was liquid helium produced in a separate helium liquefier and subsequently poured into dewars at experimental sites.

In 1933, the Narkomtyazhprom Collegium [the Board of the State Commissariat of Heavy Industry] commissioned UPTI to organize an experimental station for deep cooling (OSGO).[3] To which all technical problems associated with the application of low temperatures, in

Leiden, 1929–1930
From left to right: Ol'ga Nikolaevna Trapeznikova, Professor de Haas, Lev Vasil'evich Shubnikov

particular the development of cryogenic methods of gas separation, were to be referred for processing and solution. Shubnikov was in charge of building this station (later, Professor M. Ruěman took an active part in the OSGO operations). Due to Shubnikov's efforts a highly qualified team was assembled at OSGO in a short time to solve problems of technological importance. There, measurements were made of thermal conductivity and the mechanical properties of structural materials. Liquid-gas equilibria were investigated for binary and tertiary systems. A semi-industrial installation was built for the separation of coke gas. The work at OSGO has significantly influenced the development of cryogenic technology in the USSR.

From the very first, one of the basic study themes followed by Shubnikov at the UPTI cryogenics laboratory was superconductivity. After its discovery by Onnes in 1911, it was assumed for a long time that this effect consists of the disappearance of electrical resistance at low temperatures, i.e., a superconductor is an ideal conductor. The magnetic properties of such an ideal conductor were expected to depend on the manner of conducting an experiment. When a superconductor is cooled to $T < T_c$ in the absence of a magnetic field, switching on of the latter was not expected to lead to its penetration into the superconductor volume; whereas the cooling of a superconductor in an external magnetic field was expected to result in the "freezing-in" of the field in the superconductor. Desire to elucidate what actually does happen to the superconductor stimulated a study of its magnetic properties in the then few cryogenics laboratories in the world. Investigation of the magnetic properties of superconductors was also the goal of Shubnikov's work which he conducted jointly with his fellow workers. In 1934, Shubnikov concluded the first stage of investigations of the magnetic properties of superconductors which he conducted jointly with Yu. N. Ryabinin. These experiments studied the dependence of the induction B and the magnetic moment M on the applied magnetic field for a number of superconductors. Used in the measurements were both polycrystalline specimens and single crystals prepared at the UPTI cryogenics laboratory. The results of these measurements showed that as the external field approaches its critical value a sharp change occurs in the induction B with both increasing and decreasing fields. Thus, these experiments have verified the results of

[3]Russian acronym retained. (Transl.)

Meissner and Ochsenfeld. It should be emphasized that although the latter obtained their results somewhat earlier (Meissner effect), the Shubnikov-Ryabinin work was carried out independently and with greater detail.

After studying the magnetic properties of pure superconductors, Shubnikov and coworkers carried out detailed investigations of the magnetic properties of superconducting alloys. The results of these studies were published by Shubnikov, Khotkevich, Shepelev and Ryabinin in 1937. This work was stimulated basically by two factors: Low hysteresis observed in experiments with pure superconductors which could be attributed to imperfections in the specimens, and the absence of a large jump in the specific heat in the $Pb_{65}Bi_{35}$ alloy having a high value of the critical field at which resistance appeared. [The value of the specific heat jump was shown by Gorter to be proportional to $(dH_c/dT)^2$.] This critical field was considerably greater than the H_c of pure lead and, therefore, it was expected that the specific heat jump for this alloy would be much higher than for pure lead. The measurements of specific heat were carried out by Shubnikov and Khotkevich in 1934.[4)]

Investigations of the magnetic properties of superconducting alloys have shown that unlike the case of pure superconducting metals having a single value of the critical field H_c at which the induction and resistance sharply increase and attain their values in the normal state, in superconducting alloys at a small external field H_{c1} a sharp change occurs in the induction which subsequently increases gradually. However, specimen resistance in this case remains at zero and it reverts to its value in the normal state only when the external magnetic field attains a substantial value H_{c2}. At this magnetic field strength the induction becomes practically equal to that of the applied field. The detailed investigations of the magnetic properties of alloys, which were carried out at various temperatures for specimens with different concentrations, have shown that the magnetic field region in which the induction is other than zero and the resistance is nonexistent, i.e., a region between H_{c1} and H_{c2}, expands when the temperature decreases and the alloy concentration increases. The state in which a superconducting alloy remains in the field region between H_{c1} and H_{c2} is today referred to as the "Shubnikov phase."

The significance of the results obtained by Shubnikov and coworkers was fully borne out only twenty years after the publication of their work, at a time of intensive investigations of superconducting alloys based on the transition metals, which were occasioned by the introduction and application of these alloys in technology. In addition to this, the Ginzburg-Landau theory was advanced about that time, and used by Abrikosov to develop a theory of superconductors of the second kind.

[4)]As is known, it was subsequently shown that the magnitude of a specific heat jump of an alloy is defined not by the field H_{c2} at which resistance appears, but by the thermodynamic critical field H_c whose magnitude in an alloy is relatively small.

Today, as the superconducting alloys are finding broader practical applications, the expression "Shubnikov phase" is one of the necessary terms to characterize these properties. As is known, theoretical works have shown that the appearance of the Shubnikov phase is a consequence of the specific behavior of type II superconductors: This phase occurs when the depth of penetration of the magnetic field is greater than the coherence length and, therefore, the surface energy at a boundary between the phases will be negative; in turn, the negative surface energy will lead to enlargement of the inter-phase boundary, i.e., the alloy's transition into a mixed state.

In addition to detailed investigations of the magnetic properties of superconducting alloys, Shubnikov and coworkers also studied the special features of destruction of superconductivity in metals and alloys by current. They discovered an intermediate state occurring when the current upsets superconductivity. These measurements were conducted on cylindrical lead single crystals at $T \approx 2$ K. Together with V. I. Khotkevich, Shubnikov carried out detailed investigations of the behavior of a superconducting ring with current in it.

A number of other questions of low-temperature physics also occupied Shubnikov's time. With Lazarev, while measuring the magnetic susceptibility of liquid hydrogen, he determined the magnetic moment of a proton. This work was interesting not only because the magnetic moment of a proton was measured and found to be 2.3 ± 0.2 of the nuclear magneton, but also because the time of orientation of the nuclear spin in a magnetic field and, consequently, time for a transfer of energy, equal to 2 μH, from the spin to lattice did not exceed one second. This result refuted the theoretical work by Heitler and Teller who asserted that to transfer energy from the nuclear spin to lattice requires 10^{12}s. A new estimation of this time based on the Lazarev-Shubnikov data was made in a 1936 note published by Fröhlich and Heitler who showed that if the effect of the electron magnetic moment of an orthohydrogen molecule is taken into account, the time in question will be approximately 0.1 s.[5)]

Together with O. N. Trapeznikova, Shubnikov studied the specific heat of anhydrous chlorides of transition metals. These measurements, as also the measurement of the magnetic properties of anhydrous chlorides made by Shubnikov with S. S. Shalyt, revealed a transition of these chlorides from the paramagnetic state into a new, antiferromagnetic state which was theoretically examined by Landau in 1933.

Lev Vasil'evich Shubnikov was an exceptionally energetic and efficient man. He was always of a good and cheerful disposition and he was a decisive person. These qualities, as well as his benevolent attitude toward people, contributed to a friendly atmosphere at Shubnikov's laboratory. The laboratory personnel

[5)]Normal composition hydrogen was used: 75% orthohydrogen and 25% parahydrogen.

worked arduously and harmoniously aiding one another willingly. All those who were fortunate to work under his leadership recall with pleasure the time so spent. In addition to his scientific work, Shubnikov was also involved in an extensive teaching effort. During 1934–1937, he was a professor at the Khar'kov University where he also headed the department of general physics.

The broad range of the various experimental methods, a very high quality of the laboratory measurements and a number of unique results obtained all made the UPTI Cryogenics Laboratory—established and led by Shubnikov—one of the major cryogenic centers. The brilliant publications of Shubnikov have long ago become classics, while his name has acquired wide global recognition alongside the names of other pioneers in low-temperature physics.

I consider it a pleasant duty to express my sincere gratitude to O. N. Trapeznikova for considerable help rendered in the course of writing of this article.

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