The Life and Legacy of Pomeranchuk

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1   Introduction

The life of Isaak Yakovlevich Pomeranchuk was short (20.05.1913 – 14.12.1966). But the impact of his personality and his works on physics and physicists is remarkable.

With better luck he could live today and even participate in this conference. It is difficult to imagine what would be the theme of his talk. The 36 years without him brought drastic changes in all aspects of life, science in general and physics in particular. But many of the talks at this conference have roots in the ideas and the thrust of Pomeranchuk.

All his life he was ready to start a new journey into the world of unknown. He went on many of them. Insatiable scientific curiosity was one of his dominant passions.

2   On the way to physics

Yuzik Pomeranchuk was born in Warsaw (at that time in Russia) on the eve of the World War I. His father was a chemical engineer, mother – medical doctor. In 1918 the family moved to Rostov-on-Don, later, in 1923, – to a town Rubezhnoe in Donets Basin, where his father worked as engineer at a chemical plant. In 1927 Yuzik graduated from 7-year school and two years later from a factory - and workshop school. In 1929-31 he was a worker at chemical plant. In 1931 he left Rubezhnoe for Ivanovo, a city some 300 km North-East of Moscow, and became a first year student of the Institute of Chemical Technology. In 1932 he moved from Ivanovo Institute to the second

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course of Physical-Mechanical Department of the Leningrad Polytechnical Institute. Here he specialized in chemical physics. Fellow students recalled that Yuzik enthusiastically worked 14 hours a day and led rather ascetic life. He searched in the library answers to questions which appeared during lectures and had a special gift of clearly explaining to his friends all difficult problems.

3 Yuzik, are you a theorist?

In 1934-35 his advisor became Alexander Iosifovich Shalnikov (1905 – 1986). Many years later academician Shalnikov recalled that he started by bringing Yuzik to a room full with old vacuum pumps glass-ware and leaving him there. Two weeks later, entering the room, Shalnikov found that everything that could be broken was broken. 'Yuzik, are you a theorist?", – uttered Shalnikov. "I don't know. And what?" – was the answer.[1]

Shalnikov and his wife bought a ticket and put Yuzik on a train to Kharkov, providing him with some money and food (it was a lean year). Kharkov was known at that time as a new center of theoretical physics led by the young Lev Davidovich Landau (1908 – 1968), who spent before a few years at the Niels Bohr Institute in Copenhagen and decided to create a similar cradle for young theorists in the Soviet Union, Yuzik became one of the first students of Landau. He passed the famous "theoretical minimum exams" in two months (for many others it took years) and published his first paper on light by light scattering, together with A. Akhiezer and L. Landau in 1936 in "Nature".

Pomeranchuk was a devoted disciple of Landau. (The names Dau and Chuk were coined by Landau.) "I am ready to go after Dau to the Dickson island", said young Chuk to one of his friends. (Dickson is an island in the Arctic Ocean near the shores of Siberia, at the mouth of Yenisey.) The mutual respect and affection thread runs all through their lives.

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[1]This and future quotations are from the book "Vospominaniya o I.Ya. Pomeranchuke", Moskva, Nauka, 1988 (in Russian), which contains recollections of 83 authors and 7 scientific reviews: describing the impact of Pomeranchuk on physics of elementary particles, quantum field theory, theory of nuclear reactors, synchrotron radiation, quantum liquids and crystals, heat conductivity in dielectrics.

4 The 1936-1941 Firework

The "photon-photon" article started a firework of papers in various fields, such as cosmic rays, neutron scattering in crystals, conduction of heat and sound in dielectrics, electroconductivity of metals, superconductivity and other subjects.

The most unexpected was the discovery that there should exist an upper limit about 10^{17} eV on cosmic electron energy at the surface of the Earth due to emission of photons in the magnetic field of the Earth. Arkady Migdal recalled that when Pomeranchuk told him about his idea, he (Migdal) was convinced that such a weak field could not influence the trajectory of ultra-high energy particle. But intuition of Pomeranchuk turned out to be correct. This effect was the first in a series of famous works of Pomeranchuk on the theory of synchrotron radiation.

Among other results in condensed matter physics was the correction to Peierls $1/T$ law for heat conduction at high temperature T. "It was not pleasant, but it consoled me that I had been caught by very clever Pomeranchuk but not by somebody else", recalled Rudolf Peierls.

Not everything, on which Pomeranchuk worked at that time, was published by him. In 1941 he gave three talks at a conference held in Moscow. The program of the conference was published in "Journal of Physics of USSR". Two talks by Pomeranchuk "The production of mesotron pairs by positron annihilation" and 'The scattering of mesotrons by mesotrons" are presented by the abstracts, while the third one "Nuclear reactions inside stars" is presented by the title only.

5 Wanderings: 1937 − 1946

In 1937 under the threat of arrest Landau left Kharkov for Moscow, to join the Kapitza Institute. Pomeranchuk followed him to become an assistant lecturer at the Moscow institute of tanning industry.

The transfer to Moscow delayed Landau's arrest only by a year: in 1938 he was imprisoned. Only a letter by Peter Kapitza to Stalin saved Landau's life, he spent in the prison a year.

After Landau's arrest Pomeranchuk moved to Leningrad. In 1938-39 he is an assistant lecturer at Leningrad University, defending there in 1938 his PhD. In 1939-40 Pomeranchuk is a junior scientist at Leningrad Physical-

Technical Institute. In 1940 he comes back to Moscow as a senior scientist at Lebedev Institute and defends his DSc dissertation "Heat conductivity and absorption of sound in dielectrics". In 1941 the war started and Lebedev Institute was evacuated to Kazan. From there in 1942 Pomeranchuk was sent as a member of a group headed by Abram Isaakovich Alikhanov to Armenia. The task of the group was to initiate the construction of a station for study of cosmic rays at the Aragats mountain. They were on their way to Armenia during the Stalingrad battle. In Yerevan Pomeranchuk together with A.F. Kirpichev wrote three papers on the theory of cosmic ray showers.

In May 1943 Pomeranchuk returned to Moscow to become a member of the Kurchatov team, working on the first Soviet nuclear reactor. He worked with Igor Vasilyevich Kurchatov at what was called Lab. No.2 and is now called Kurchatov Institute till the beginning of 1946. For the rest of his life he stayed at what then was called Lab. No.3 and is now called ITEP being the founder and head of the ITEP theory division. Also in 1946 Pomeranchuk became Professor of theoretical physics at Moscow Mechanical Institute (at present MEPHI).

6   Neutrons in 1940s

Since 1943 Pomeranchuk was the leader of nuclear reactor theory in Soviet Union. He developed the theory of exponential experiments which allowed Kurchatov to measure the neutron absorption in moderator and the value of moderation length.

Neutrons became dominant in his work in 1940s. Together with I. Gurevich he created a theory of resonance absorption of neutrons in heterogeneous nuclear reactor with natural uranium. The construction of the first Soviet reactor completed in 1946 was based on this theory. (It was published as a report at the International conference on peaceful applications of atomic energy in 1955.) The theory of neutron absorption in homogeneous media was developed by Pomeranchuk and Akhiezer in the manuscript "Introduction to the theory of neutron multiplying systems", ITEP, 1947. It served as a basic manual for construction of Soviet nuclear reactors for many years. I remember using it as a novice calculating nuclear reactor for China in the middle of 1950s. At that time its single copy was worn out to pieces. In 2002 the book was ultimately edited and published by B. Ioffe and A. Gerasimov. A part of this manuscript was published as a separate book: A. Akhiezer

and I. Pomeranchuk "Certain problems of nuclear theory" in 1948 and then in 1950. Theory of nuclear reactors was the main practical task of the theory division created at ITEP by Pomeranchuk who recruited V. Berestetsky, A. Galanin, B. Ioffe, A. Rudik. The non-reactor physics was considered as a kind of a hobby.

7   "Hobby problems" in 1940s

The number, variety and quality of these "hobby problems" is quite impressive: Pomeranchuk continued his research on phonons (heat and sound conduction), on cosmic rays (on the atmospheric showers), on spectrum of synchrotron radiation at electron accelerators. He published two articles: on maximal energy of electrons in a betatron (1944, together with D. Ivanenko) and on spectrum of synchrotron radiation (1946, together with L. Artsimovich). By the way, V. Vladimirsky found in 1948 that maximal energy of showers produced by cosmic electrons in the atmosphere can be much larger than the Pomeranchuk limit for a primary electron, because above 10^{18} eV the quantum of radiation carries substantial part of electron's energy. Pomeranchuk helped him to publish this result.

New themes appeared:

The first theme: liquid helium, in particular helium-3. In 1948 he established that both ^{3}He and ^{6}He admixtures to ^{4}He belong to normal (non-superfluid) component of liquid helium. This research culminated by the famous 1950 paper in which Pomeranchuk has put forward the idea that the entropy of helium-3 is smaller in liquid state than in the solid one and suggested his method of reaching microkelvin temperatures. (The nuclear spins of ^{3}He should be aligned in the liquid phase (due to exchange forces) and not aligned in the solid phase. Hence entropy of the latter is larger.)

Implementation and development of these ideas were crowned in 1996 by Nobel Prize to David Lee, Douglas Osheroff and Robert Richardson for their discovery of superfluidity in helium-3. We have the privilege to listen today to the talk of Professor Osheroff.

The second theme: 1945, the finite size atomic nuclei with $Z > 137$. Y.A. Smorodinsky who coauthored this article recalled that Pomeranchuk's enthusiastic exclamation "It would be great to collide two uranium nuclei!" was met by laughter: nobody believed in such experiments. They were done much later in Darmstadt.

The third theme: 1948, selection rules in the decay of positronium (the three photon decay of orthopositronium and two photon decay of parapositronium).

8 Arzamas-16

Early in 1950 Pomeranchuk was sent to the atomic weapon center at Arzamas-16. The order was signed by Stalin. Pomeranchuk longed for his family (wife and his stepdaughters) and for "hobby physics". He used to come to N. Bogolubov (they lived in the same hostel) to discuss with him how to revoke the order. Bogolubov entertained him with a cup of excellent strong coffee and aphoristically uttered: "Orders are not revoked, usually they are forgotten". Within a year Pomeranchuk was again in Moscow, at ITEP.

9 QFT and zero charge

Pomeranchuk enthusiastically reacted to the breakthrough in quantum field theory. In 1951 he set up a special seminar to study the relativistic covariant technique originated by Feynman, Dyson, Schwinger and others. He used it in two different ways: to elucidate the basic problems of the renormalization procedure and to apply it to various specific phenomena.

On the first way he and Landau discovered the fundamental difficulty which they dubbed "zero charge", and which is now referred to as "triviality problem". They found that any finite value of "bare charge" (at short distances) results in a vanishing "physical charge", i.e. in the absence of interaction (at observable distances). This property was established first in quantum electrodynamics, then in various types of meson theories. An important role at this stage was played by V. Sudakov and K. Ter-Martirosyan who joined ITEP in the 1950's.

Only in the early 1970's it became clear that the non-abelian gauge theories do not suffer from this fatal disease. As you go to shorter distances the non-abelian charges decrease providing "asymptotic freedom". But even today the disease discovered by Pomeranchuk and Landau is not eradicated. It is hiding in the Higgs sector of the electroweak interaction. The fight against this disease is one of the driving forces of the modern field theory.

10 Applications of QFT and S-matrix

In spite of unsolved "zero charge" basic inconsistency Pomeranchuk vigorously applied QFT to various phenomena which did not "feel" this inconsistency. Together with A. Galanin in 1952 he calculated the energy shift in muonic atoms due to polarization of vacuum by virtual photon. He modified in 1951 the approach suggested by E. Fermi to multiple production of pions at high energies.

Pomeranchuk paid great attention to the characteristic time intervals at which various processes took place. In 1953 together with L. Landau he found how the standard Bethe-Heitler formula for Bremsstrahlung cross section is modified in a medium. The characteristic time of the process is $E^2/m^2\omega$, where E – energy of the electron, m – its mass, and ω – frequency of the photon. At high enough energy the emission length becomes so large that multiple scattering is essential. Further refinement of the problem was done by A. Migdal. The LPM-effect is under active study even at present.

In 1953 Pomeranchuk was elected corresponding member of Soviet Academy. He became full member (academician) in 1964.

In 1950's Pomeranchuk analyzed diffraction processes in the collisions of nucleons at high energies and peripheral collisions with one-pion and two-pion exchange. Here he relied on dispersion relations, which follow from such general principles as causality and conservation of probability (analiticity and unitarity of S-matrix).

On the basis of dispersion relations and of assumption that the radius of a particle does not increase with its energy he proved in 1958 his famous theorem, according to which the cross-sections of a particle and its antiparticle on a given target are equal to each other at asymptotically high energy.

Pomeranchuk theorem gave a strong impetus to experiments and theory in particle physics, to building high energy accelerators and colliders. In 1958 the highest energy was about 1 GeV. Today it is measured by TeVs.

11 Pomeron

Theoretical analysis has shown quite soon that the assumption that the radius of, say, proton does not depend on energy, is too naive. It should increase as logarithm of energy. But asymptotic equality of particle and antiparticle cross-sections discovered by Pomeranchuk remained valid.

The asymptotic behaviour in s-channel depends on the angular momentum $j(t)$ of quasi-particles exchanged in t-channel ($s = E^2$, $t = q^2$): $s^{j(t)}$. This angular momentum depends on t, forming in the plane j, t the so-called Regge-trajectory. Hadrons with integer spin (mesons) and half-integer spin (baryons) lie on these trajectories.

The behaviour of total cross-section depends on the value of j at $t = 0$ of the trajectory with all quantum numbers (charge, isospin, C-parity) of the vacuum. It was M. Gell-Mann who suggested to call this vacuum trajectory the Pomeranchuk trajectory. The corresponding quasi-particle is referred to as pomeron in the literature.

Pomeranchuk published about a dozen articles on reggeonic theory of strong interactions (most of them with Vladimir Naumovich Gribov (1930-1997)). The first of these articles was published in 1962, the last – after Pomeranchuk passed away.

During last four years of Pomeranchuk's life his collaboration with Gribov was fantastically intense. Gribov, who lived in Leningrad, regularly came to ITEP, a few times Pomeranchuk took train to Leningrad. Their discussions in Pomeranchuk's office at ITEP lasted late into the night. Both of them were heavy smokers. A cigarette was lighted from the previous one. The smoke in the room was thick. Many years later J. Björken wrote that those brilliant works had cleared the mist in the minds of theorists at Berkeley and brightly demonstrated the extremely high level of research in certain fields in the Soviet Union.

12   His disciples

Pomeranchuk influenced the development of physics not only through his articles. He was a Great Teacher. Being the head of theory division at ITEP, he at the same time was a Professor of theoretical physics at Moscow Engineering Pysics Institute (MEPHI), which is hosting this memorial conference. His former students were A. Rudik, I. Kobzarev, M. Terentyev, Yu. Nikitin, A. Kaidalov, Yu. Simonov, Yu. Vdovin, I. Dremin, V. Mur, E. Zhizhin, A. Berkov, B. Karnakov, I. Zuckerman and among many others myself.

When in 1951 Pomeranchuk was designated to become the head of the theory group in Dubna he brought with him one of his MEPHI students S. Bilenky. For about a year Pomeranchuk used to come to Dubna every week

as a part time job. Among his disciples there was L. Lapidus. Pomeranchuk strongly influenced the work of R. Ryndin and of many experimentalists. According to recollections of B. Pontecorvo, V. Dzhelepov and many others each visit by Pomeranchuk was a remarkable event in the life of physicists in Dubna, who remembered his improvised seminars for many years.

ITEP theory division attracted also students from Moscow University. The most prominent of them are B. Ioffe, M. Marinov and V. Popov.

The personality of Pomeranchuk is unforgettable to everybody who had the luck to work with him, to listen to his lectures, or even only to meet him. He was extremely devoted to physics and at the same time he was very human. Great integrity was fused in him with sincere sympathy, with rare sense of humor. Many of his jokes help us at ITEP to live through hard times.

13 Fight against cancer

Pomeranchuk did not look an athlete, but he was strong, of great endurance and of great courage. In the fall of 1965 doctors discovered that he was fatally ill: cancer of esophagus. For more than a year he underwent chemotherapy, radiotherapy, surgery (gastrotomy). But he continued to do physics in hospitals and at home till his last day.

During the tragic days and nights of his illness Pomeranchuk was cared for by his stepdaughter Marina who fought for his life with inexhaustible energy. Today Marina Alexeevna Ivanova-Pomeranchuk is with us in this hall.

Being treated by gamma-rays he thought about the Bragg peak in stopping proton beam. It was obvious for him that protons, unlike electrons or gamma-rays, would deliver most of their energy at the end of their track inside the tumor. He summoned physicists from ITEP and Dubna together with radiologist in the Oncological Center to start the program of proton therapy at the existing proton accelerators. Unfortunately it was too late to help him. But he thought about others. The first medical proton beam started to operate at ITEP in 1969. More than 3000 patients were successfully treated at ITEP. Recently special centers for proton therapy were built in Western Europe and USA.

14   Pomeranchuk Prize

In 1998 Pomeranchuk Prize was established at ITEP. Up to now the international jury awarded it to ten physicists:

A. Akhiezer, S. Drell (1998)

K. Ter-Martirosyan, G. Veneziano (1999)

E. Feinberg, J. Bjorken (2000)

L. Lipatov, T. Regge (2001)

L. Faddeev, B. DeWitt (2002)

Professor B. DeWitt will receive the Prize today. Professor L. Faddeev – at the ITEP International Winter School in February.

The names of 2003 prize winners will be announced on 20th of May 2003, Pomeranchuk's 90th birthday.

The constellation of laureates sheds a special light on the legacy of Pomeranchuk: on his formulas and ideas in various fields of physics, on his style of research marked with deep intuition, ingenuity and hard work, on his devotion to physics, his integrity, his striving to the heart of the matter, combined with painstaking attention to details, his gift of a great teacher who shared his enthusiasm and knowledge with his disciples and peers.

15   Addendum

List of scientific publications by I.Ya. Pomeranchuk[2]

1936 – 1941

1. On properties of metals at very low energies. (With L.D. Landau.) ZhETF **7** (1937) 379; Phys. Zs. Sowjet. **10** (1936) 649. (SW, **1**, 1).[3]

2. Light by light scattering. (With A.I. Akhiezer and L.D. Landau.) Nature **138** (1936) 206 (SW, **2**, 33).

3. Coherent scattering of γ-rays by nuclei. (With A.I. Akhiezer.) ZhETF **7** (1937) 567; Phys. Zs. Sowjet. **11** (1937) 478 (SW, **2**, 34).

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[2]This is a translation into English of a list published in the third volume of Scientific Works (SW) by I.Ya. Pomeranchuk, "Nauka", Moskva, 1972 (in Russian).

[3]This is a reference to the volume and the number of the article in SW.

4. On the scattering of slow neutrons in a crystal lattice. ZhETF **8** (1938) 894; Phys. Zs. Sowjet. **13** (1938) 65 (SW, **1**, 25).

5. Critical field in superconductors of small size. ZhETF **8** (1938) 1096 (SW, **1**, 2).

6. On the maximal energy which the primary electrons of cosmic rays can have on the earth's surface due to radiation in the earth's magnetic field. ZhETF **9** (1939) 915; J. Phys. SSSR **2** (1940) 65 (SW, **2**, 41).

7. The influence of a magnetic field on the electrical conductivity of bismuth single crystals at low temperatures. (With B.I. Davydov.) ZhETF **9** (1939) 1294; J. Phys. USSR **2** (1940) 147 (SW, **1**, 3).

8. On the end of mesotron track in Wilson chamber. (With A.B. Migdal.) Dokl. AN SSSR **27** (1940) 652; Phys. Rev. **57** (1940) 934 (SW, **2**, 42).

9. The thermal conductivity of the paramagnetic dielectrics at low temperatures. ZhETF **11** (1941) 226; J. Phys. USSR **4** (1941) 357 (SW, **1**, 7).

10. On the thermal conductivity of dielectrics at the temperatures higher than the Debye temperature. ZhETF **11** (1941) 246; J. Phys. USSR **4** (1941) 259 (SW, **1**, 8).

11. Sound absorption in dielectrics. ZhETF **11** (1941) 455; J. Phys. USSR **4** (1941) 529 (SW, **2**, 9).

12. The production of mesotron pairs by positron annihilation. J. Phys. USSR **4** (1941) 277.

13. The scattering of mesotrons by mesotrons. J. Phys. USSR **4** (1941) 277.

14. Nuclear reactions inside stars. J. Phys. USSR **4** (1941) 285.

15. On conduction of heat in dielectrics. Phys. Rev. **60** (1941) 820 (SW, **1**, 10).

1942 – 1946

16. On conduction of heat in dielectrics below Debye temperature. ZhETF **12** (1942) 245; J. Phys. USSR **6** (1942) 237; Izvestiya AN SSSR, physical series **6** (1942) 77 (SW, **1**, 11).

17. Conduction of heat in dielectrics at high temperatures. ZhETF **12** (1942) 419; J. Phys. USSR **7** (1943) 197 (SW, **1**, 12).

18. Dependence of sound absorption in dielectrics on frequency and temperature. J. Phys. USSR **7** (1943) 266 (SW, **1**, 13).

19. Coulomb forces and neutron structure. Dokl. AN SSSR **41** (1943) 162 (SW, **2**, 54).

20. Spectrum of soft component in the air at high energies. (With A. Kirpichev.) Dokl. AN SSSR **41** (1943) 19 (SW, **2**, 43).

21. On the theory of transition effect in cosmic rays. (With A. Kirpichev.) Dokl. AN SSSR **42** (1944) 396 (SW, **2**, 44).

22. On the theory of absorption of infrared rays in center-symmetrical crystals. ZhETF **13** (1943) 428; J. Phys. USSR **7** (1943) 262 (SW, **1**, 14).

23. On the screening of effective cross sections of Bremsstrahlung and pair production calculated with experimental data on atomic form factors. (With A. Kirpichev.) Dokl. AN SSSR **45** (1944) 301 (SW, **2**, 45).

24. Scattering of mesons strongly interacting with nucleons. Dokl. AN SSSR **44** (1944) 13 (SW, **2**, 55).

25. On the conduction of heat in magnetically cooled salts. (With A.I. Akhiezer.) J. Phys. USSR **8** (1944) 216 (SW, **1**, 15).

26. On thermal equilibrium of spins and lattice. (With A.I. Akhiezer.) ZhETF **14** (1944) 342; J. Phys. USSR **8** (1944) 206 (SW, **1**, 16).

27. On the interpretation of experimental data on large avalanche showers. ZhETF **14** (1944) 252; J. Phys. USSR **8** (1944) 17 (SW, **2**, 46).

28. Radiation of fast electrons in magnetic field. (With L.A. Artsimovich.) ZhETF **16** (1946) 379; J. Phys. USSR **9** (1945) 267 (SW, **2**, 48).

29. On the maximum energy attainable in a betatron. (With D.D. Ivanenko.) Dokl. AN SSSR **44** (1944) 343 (SW, **2**, 47).

30. On energy levels in systems with $Z > 137$. (With Ya.A. Smorodinsky.) J. Phys. USSR **9** (1945) 97 (SW, **2**, 35).

31. On the conduction of heat in bismuth. (With A.I. Akhiezer.) ZhETF **15** (1945) 587; J. Phys. USSR **9** (1945) 93 (SW, **1**, 4).

32. On elastic scattering of fast charged particles by nuclei. (With A.I. Akhiezer.) ZhETF **16** (1946) 396; J. Phys. USSR **9** (1945) 471 (SW, **3**, 96).

33. On elastic scattering of neutrons with energy of a few Kelvins in liquid helium II. (With A.I. Akhiezer.) ZhETF **16** (1946) 391; J. Phys. USSR **9** (1945) 461 (SW, **1**, 18).

34. Radiation of relativistic electrons in magnetic field. Izv. AN SSSR, physical series **10** (1946) 316 (SW, **2**, 49).

1947 – 1951

35. On scattering of slow neutrons in crystals. (With A.I. Akhiezer.) ZhETF **17** (1947) 769; J. Phys. USSR **11** (1947) 167 (SW, **1**, 28).

36. Generalization of the limiting λ-process and ambiguity of elimination of infinities in quantum theory of elementary particles. ZhETF **17** (1947) 667; J. Phys. USSR **76** (1949) 298 (SW, **2**, 56).

37. On the theory of resonance scattering of particles. (With A.I. Akhiezer.) ZhETF **18** (1948) 603 (SW, **1**, 29).

38. On refraction of neutrons. (With A.I. Akhiezer.) ZhETF **18** (1948) 475 (SW, **1**, 30).

39. On the motion of foreign particles in helium II. (With L.D. Landau.) Dokl. AN SSSR **59** (1948) 669 (SW, **1**, 19).

40. On fluctuation of ionization ranges. ZhETF **18** (1948) 759 (SW, **2**, 50).

41. Introduction into the theory of neutron multiplicating systems (reactors) (With A.I. Akhiezer.) ITEP Report, M., 1947; Moscow, Izd.AT, 2002.

42. Selection rules for annihilation of electrons and positrons. Dokl. AN SSSR **60** (1948) 213 (SW, **2**, 36).

43. Certain problems of nuclear theory. (With A.I. Akhiezer.) M., Gostekhizdat, 1st edition, 1948; 2nd edition, 1950, 416 pp.

44. Effect of impurities on the thermodynamical properties of velocity of second sound in He II. ZhETF **19** (1949) 42 (SW, **1**, 20).

45. A remark on scattering of particles with vanishing energy. ZhETF **18** (1948) 1146 (SW, **1**, 31).

46. Lifetime of slow positrons. ZhETF **19** (1949) 183 (SW, **2**, 37).

47. Radiation in the collision of fast neutrons with protons. (With I.M. Shmushkevich.) Dokl. AN SSSR **64** (1949) 499 (SW, **3**, 80).

48. On the determination of non-electromagnetic interaction between electrons and neutrons. (With A.I. Akhiezer.) ZhETF **19** (1949) 558 (SW, **1**, 32).

49. On the β-decay of neutron. (With V.B. Berestetsky.) ZhETF **19** (1949) 756 (SW, **2**, 67).

50. Electromagnetic radiation caused by exchange forces. (With I.M. Shmushkevich.) Dokl. AN SSSR **70** (1950) 33 (SW, **3**, 81).

51. On the theory of liquid ^{3}He. ZhETF **20** (1950) 919 (SW, **1**, 21).

52. Exchange collisions of fast nucleons with deuterons. I. ZhETF **21** (1951) 1113 (SW, **3**, 82).

53. Exchange collisions of fast nucleons with deuterons. Dokl. AN SSSR **78** (1951) 249 (SW, **3**, 83).

54. On conversion of charged π-meson into a neutral meson in collisions with proton and deuteron. (With V.B. Berestetsky.) Dokl. AN SSSR **77** (1951) 803; ZhETF **21** (1951) 1333 (SW, **3**, 84).

55. On the theory of production of many particles in a single act. Dokl. AN SSSR **78** (1951) 889 (SW, **3**, 105).

56. Capture of π-particle in a deuteron. Dokl. AN SSSR **80** (1951) 47 (SW, **3**, 86).

57. On collisions of π-mesons with deuterons. (With V.B. Berestetsky.) Dokl. AN SSSR **81** (1951) 1019 (SW, **3**, 88).

58. The conduction of heat in a fully ionized gas at high temperatures. (With V.B. Berestetsky and B.L. Ioffe) 1951 (SW, **1**, 345).

$$1952 - 1956$$

59. On the theory of capture of π-particles by deuteron. ZhETF **22** (1952) 129 (SW, **3**, 85).

60. Exchange collisions of flat nucleons with deuterons. ZhETF **22** (1952) 624 (SW, **3**, 87).

61. On electrons emitted in the process of capture of μ-mesons on atomic levels. (With B.L. Ioffe.) ZhETF **23** (1952) 123 (SW, **2**, 38).

62. On the spectrum of μ-mesohydrogen. (With A.D. Galanin.) Dokl. AN SSSR **86** (1952) 251 (SW, **2**, 39).

63. On the emission of high energy γ-quanta in collisions of fast neutrons with protons. (With I.M. Shmushkevich.) Dokl. AN SSSR **87** (1952) 385 (SW, **3**, 89).

64. On the paramagnetic dispersion. (With A.I. Akhiezer.) Dokl. AN SSSR **87** (1952) 917 (SW, **1**, 17).

65. Emission of γ-quanta in collisions of fast π-mesons with nucleons. (With L.D. Landau.) ZhETF **24** (1953) 505; CERN Symp. **2** (1956) 159 (SW, **3**, 97).

66. On external (diffraction) generation of particles in nuclear collisions. (With E.L. Feinberg.) Dokl. AN SSSR **93** (1953) 439 (SW, **3**, 98).

67. Limits of applicability of the theory of Bremsstrahlung by electrons and production of pairs at high energies. (With L.D. Landau.) Dokl. AN SSSR **92** (1953) 535 (SW, **2**, 51).

68. Electron-avalanche processes at superhigh energies. (With L.D. Landau.) Dokl. AN SSSR **92** (1953) 735 (SW, **2**, 5).

69. Emission of photon in the capture of a fast proton by nucleus. (With A.I. Akhiezer.) Dokl. AN SSSR **94** (1954) 821 (SW, **3**, 99).

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