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V I Veksler and the development of nuclear physics in the Soviet Union

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1. Introduction

Celebrating the 100th anniversary of the birth of Vladimir Iosifovich Veksler (born March 4, 1907), we shall briefly follow how he came to be a prominent scientist. He cast his lot with the development of nuclear and elementary particle physics in this country, where he was among the first researchers of cosmic rays in the mid-1930s. After World War II, Veksler headed large research teams at FIAN and JINR studying the microworld problems with the aid of accelerators built within the decade from 1948 to 1957, based on the phase stability principle he had discovered in 1944. The first Soviet 30-MeV electron accelerator (S-3 synchrotron) was put into operation by a group of enthusiasts led by Veksler in 1948; for almost 40 years, it remained the main instrument of physical research in the Laboratory of Photonuclear Reactions, FIAN (since 1971 — the Institute for Nuclear Research, USSR AS).

The history of the Laboratory of Photonuclear Reactions (LPNR, FIAN) is inseparable from the name of Vladimir Iosifovich Veksler. It was established in early 1948 after the first Soviet (and third in the world) electron accelerator (30-MeV S-3 synchrotron) had been commissioned at the Etalon Laboratory on the territory of the old FIAN building 'B' (3rd Miusskaya str., 3). The laboratory was so named for reasons of secrecy, since its nuclear researchers worked for the Soviet atomic project.

The commissioning of the S-3 synchrotron marked the completion of the first period during which Veksler matured as a scientist and arrived at the decision to develop a novel approach in experimental nuclear physics for investigations into the structure of the atomic nucleus and elementary particles. The idea was to pass from cosmic ray studies, where Veksler had already obtained totally new results, to experiments at accelerators of elementary particles with an energy comparable with the primary energy of cosmic radiation.

The works by Vladimir Iosifovich Veksler (hereinafter V I) in many respects governed the rapid development of nuclear physics at FIAN and in the Soviet Union.

Physical studies in the early 20th century were carried out at the Academy of Sciences and many other institutions (Physical-Technical Institute in Leningrad, P N Lebedev Physical Laboratory in Moscow). The Academy and the Physical-Mathematical Institute were based in Leningrad. The largest Seismic Department of the latter institute was designated as a separate research institution in October 1928. After that, the staff of the remaining Physical-Mathematical Institute comprised the director, two heads of departments (with T P Kravets at the head of the Physical Department), and four research workers. S I Vavilov, appointed head of the Physical Department in 1932, started its reorganization. In the summer of 1934, the Soviet Government authorized the removal of the Academy, including the Physical-Mathematical Institute, from Leningrad to Moscow. Here, the institute occupied an old building (3rd Miusskaya str., 3) constructed with funds of the Moscow public for the laboratory of P N Lebedev in 1912. Very soon, mathematicians established their own institute, and the Physical-Mathematical Institute was redesignated under its present name, the P N Lebedev Physical Institute. The name Lebedev connected the old academic physical school with the new Moscow one [1, p. 43].

V I was shaped into a scientist in those years. He finished the 9-year school at an orphanage in 1925 and was given a Komsomol assignment to a job at the Sverdlov printed-cotton factory, first as a pupil and then as an electrician's assistant. In 1927, the Moscow City Committee of the Young Communist League recommended him for entrance into the Electrotechnical Department of the Plekhanov Institute of National Economy. Reorganization of the Institute forced Veksler and his fellow students to move to the Moscow Power Engineering Institute (MPEI). Veksler graduated from MPEI in 1931 by passing finals without attending lectures and was awarded a diploma in X-ray technology. When completing his studies at MPEI he simultaneously was accepted in 1930 for employment at the All-Union Electrotechnical Institute (AUEI) where he successively occupied the positions of laboratory assistant, senior laboratory assistant, research worker and senior researcher, and head of laboratory. In 1934, Veksler defended his thesis for the degree of Candidate of Sciences, entitled "Measurement of X-ray intensity with the help of Geiger–Müller counters and a discharge chamber" (Autobiography of V I Veksler, 11.02.1953) [2].

At that time, many instruments had to be hand-made. In the beginning, V I assembled Geiger counters, and thereafter proportional counters. He worked an unusually short way up from junior undergraduate to candidate of sciences and from laboratory assistant at the research institute to the head of laboratory.

Further work by V I at FIAN was equally successful. On Academician S I Vavilov's recommendation he proceeded since September 1, 1936 to postgraduate (postdoctoral in the terminology of those times) studies in his Laboratory of the Atomic Nucleus (LAN). Its staff included only a few young specialists who later became widely known scientists (I M Frank, L V Groshev, P A Cherenkov, S N Vernov, M A Markov, N A Dobrotin, and some others). Most of them studied cosmic rays. These investigations were carried out in the framework of the Elbrus Complex Scientific Expedition (ECSE) organized by the Institute of Theoretical Geophysics and comprising physiologists, biochemists, meteorologists, and physicists. Soon after joining FIAN, V I was appointed to head a group of physicists studying cosmic rays. Measurements were made at altitudes from 2,200 m (Terskol) to 4,200 m (Priyut 11) above sea level, and, incidentally, at 5,300 m (Elbrus saddle) in 1937–1940. All instruments, mostly consisting of proportional counters designed by V I, were made at FIAN. They were brought to the mountains in early summer, and measurements continued till autumn. The delivery of equipment was a real challenge, the Krugozor and Priyut 11 measuring stations being accessible only by donkey. In order to conduct studies at higher altitudes, the researchers had to climb mountains with a load of instruments on their backs or resort to the services of carriers [3]. The investigations demonstrated that cosmic rays at these altitudes contained many secondary particles heavier than electrons; they were identified as slow mesons. Veksler defended his thesis "Heavy particles in cosmic rays" for Doctorate of Sciences in 1940. At that time, these studies were at the front line of nuclear physics. In 1935, Hideki Yukawa predicted the mesotron (the meson, according to the universally accepted terminology introduced by W Heisenberg). In 1937, photoplates elevated in a balloon revealed traces of particles heavier than electrons.

While working in the Elbrus Expedition, V I was appointed deputy head of LAN and a member of the FIAN Scientific Council (decision of the Presidium of USSR Academy of Sciences dated 17 May 1938). More recently, on 25 November 1938, the USSR AS Presidium adopted a resolution of paramount importance for the development of nuclear physics. The document, entitled "On the organization of atomic nucleus research in the Academy of Sciences", proposed: (...)

"4. To apply to the USSR Council of People's Commissars for the permission to begin building of new premises for the Physical Institute in 1939 in order to concentrate nuclear physics research in Moscow in the near future... .

7. To set up a permanent commission on the atomic nucleus under the aegis of the Division of Physical-Mathematical Sciences of USSR Academy of Sciences comprised of

(1) Acad. S I Vavilov, chairman,
(2) Acad. A F Ioffe,
(3) Prof. I M Frank,
(4) Prof. A I Alikhanov,
(5) I V Kurchatov,
(6) Shpetnyi (Physical-Technical Institute, Khar'kov),
(7) V I Veksler, secretary... ."

Inclusion of V I in the FIAN-based 'cyclotron team' organized in 1940 on the initiative of S I Vavilov for the construction of a cyclotron marked his actual passage from cosmic ray research to the development of particle accelerators. The team also comprised S N Vernov, L V Groshev, P A Cherenkov, and E L Feinberg (a theorist).

The world's first accelerator, a 1.2-MeV proton cyclotron, was developed by E Lawrence at the Berkeley Laboratory. Attempts to reach higher energies (60 MeV) at such facilities failed because the particle beam disintegrated after proton acceleration up to 20 MeV. The first Soviet cyclotron, with a $\sim$ 1-m poleface diameter of the magnet, was constructed by I V Kurchatov at the Physical-Technical Institute in Leningrad, and put into operation in 1940. Calculations made by the cyclotron team showed that the upper energy limit for accelerators of this type equaled 25 MeV. Further work had to be stopped after the war broke out.

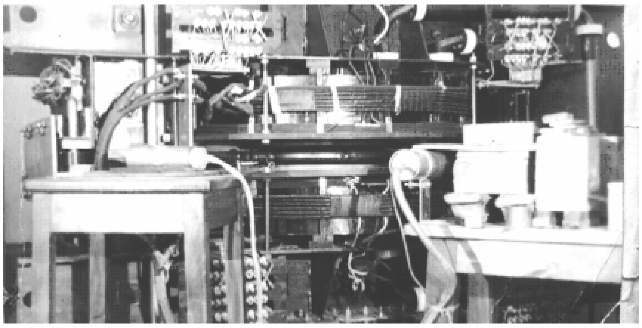
FIAN was evacuated to Kazan' where physicists had to focus on defense-oriented research. Discussions about ways of overcoming the relativistic barrier limiting the energy of accelerated particles resumed after the scientists returned to Moscow. V I did not stop thinking of accelerators with energies exceeding those in cyclotrons by a few orders of magnitude, despite being very busy with the preparations for the first Pamirs expedition of 1944 [3]. At the beginning of 1944, V I came to understanding how to utilize the relativistic effect for surmounting the energy barrier. The idea brought him to the discovery of a new principle of particle acceleration — the principle of phase stability. He published the first short communication "A new method of relativistic particle acceleration" in *Doklady Akademii Nauk SSSR* No. 8 (1944). It concluded as follows: "This phase stability automatically conditioned by the fact that the time interval between two successive accelerations depends on the accelerating voltage is a common property of accelerators of the given type; it permits (at least in principle) achieving acceleration in a variety of ways, for example, even in the case when the magnetic field grows with time."

The second paper under the heading "On the new method of acceleration of relativistic particles" [*DAN SSSR* No. 9 (1944)] described the principle of phase stability in a time-varying alternating magnetic field. V I referred to constant-field accelerators as microtrons; alternating-field accelerators were called synchrotrons as suggested by McMillan, who independently discovered the phenomenon of phase stability one year after VI. Veksler was eager to immediately start realization of his idea despite the difficult situation in the country and a total lack of experience with the creation and exploitation of accelerators. Such behavior was very typical for all his work.

2. Construction and commissioning of S-3 synchrotron (1945 – 1947)

The development of the first accelerator encountered unbelievable difficulties. It required large-tonnage electromagnets with coils passing an alternating current, and powerful high-frequency and high-vacuum systems then absent in the country. Soon after victory in World War II (1945), the Soviet Atomic Project, aimed at the creation of the USSR's own nuclear weapons, was launched. It gave a powerful impetus to the development of the atomic industry and nuclear physics in the shortest possible time. A governmental resolution of 1946 authorized incorporation of Veksler's newly organized laboratory into the atomic project for the construction of accelerators and the rapid development of nuclear physics. It was named Etalon Laboratory for reasons of secrecy. Two new buildings were soon erected close to the old FIAN premises (Miusskaya str.), one for Veksler's laboratory (building 'B'), the other for LAN also included in the atomic project.

In 1946, the laboratory headed by V I started to design a 30-MeV electron synchrotron. B L Belousov, recently graduated from Moscow State University Department of Physics, was accepted for employment as construction group leader. E L Feinberg and his postgraduate student M S Rabinovich, theoretical physicist, made calculations. The latter had to find out conditions for beam stability in the future accelerator. In mid-1946, Belousov's group included only two people: engineer E G Gorzhevskaya, and laboratory assistant I D Kedrov. B S Ratner (a pre-war MPEI graduate) joined it after demobilization from the army in June 1946. At the end of 1946, the synchrotron group comprised 19 specialists. By that time, they had not only assembled the machine but also checked all its systems and undertook the first test runs. S I Vavilov and V I managed to have an electromagnet fabricated at the Moscow Transformer Plant, and a vacuum chamber at the Institute for Physical Problems. The magnet was installed on the second floor, together with the vacuum chamber, pumping system, storage battery connected to the resonance circuit, and control panel. The high-voltage transformer feeding the magnet was placed beneath it on the first floor. At the beginning, it was planned to use the available radioactive source of electrons as the injector. As the work proceeded, the decision was taken to preliminarily accelerate electrons to $\sim$ 3 MeV in the betatron mode by the vortical electric field, and thereafter to a maximum energy of 30 MeV in the synchrotron regime. For this purpose, a core from pieces of permalloic wire insulated with a bakelite lacquer coating and a coil creating such field were assembled and placed in the center of the magnet; a correcting winding was mounted on the core. The position of



S-3 synchrotron prior to commissioning in late 1947 (viewed from the beam output).

the equilibrium betatron orbit was determined by the minimum of electric field gradient measured very accurately by the 'zero' method with the aid of coils wound around a plexiglass washer, which was placed along the radius of the magnet gap; the washer was driven by the correcting winding mounted on the core. Beam focusing was achieved by the choice of the poleface shape which ensured the desired dependence of the magnetic field on the magnet radius. It was found by V E Pisarev using a special magnet. The high-frequency electric field was set up by the efforts of E M Moroz, A V Belyak, and N G Kotel'nikov. It was first planned to use a built-in resonator that necessitated cutting the accelerating chamber. In the end, this operation was obviated by superimposing two halves of the resonator insulated by polystyrol spacers on the chamber. This saved a month of work. V G Larionova developed a method for coating the inside of the chamber with a thin silver layer to remove the electric charge of electrons that escaped capture during acceleration and accumulated on the inner surface. A slot in the conducting layer of the cavity helped to get rid of Foucault currents. A 5-μs pulse with a 30-kV amplitude was applied to the injector. Each acceleration cycle started at a zero magnetic field governed by a pulse from the coil wound around the permalloic core in the magnet gap. The time shift between injection and feeding of the accelerating electric field was varied by means of a forming device. It was made in the laboratory, as was most other equipment.

Test runs of the accelerator in the betatron mode started in the autumn of 1946 and continued for about two months. All its systems were developed operationally during this period, including reduction of phase asymmetry of the magnetic field, and improvement of vacuum instrumentation. For all that, a pulse of electrons injected into the chamber disintegrated after a single turn, and the absence of an output beam remained unexplained.

Leaders of the Soviet Atomic Project put strong pressure on VI. After a time, V I made the brave and important decision to cease further attempts to put the existing machine into operation and instead to construct its improved version. The team analyzed all weak points of the assembled accelerator and arrived at the conclusion that an electromagnet was needed with a much greater effective volume. It was one of the few components to be manufactured by industry. Advantages of incorporating the Etalon Laboratory into the atomic project became apparent in the first half of 1947. More funds were available, supplies improved, personnel increased, and construction of the new building was completed. A specialized design office was established at the Moscow Transformer Plant to develop electromagnets for accelerators.

A new electromagnet was designed and manufactured following technical task orders worked out by the laboratory; it was bigger than the preceding one and had special coils in the interpole gap to compensate for phase asymmetry. Many units of the synchrotron were upgraded, based on the previous experience. Glass accelerating chambers having a larger ellipsoid cross section than the initial ones were preformed at FIAN workshops and manufactured at a glass works. The brothers Voronkov, glass-blowers for FIAN, welded semirings and sealed in metallographic sections necessary for mounting the injector and the target and for pumping down the chamber. Thereafter, the chamber was annealed in a special electrically heated furnace. Yu S Ivanov constructed a new vacuum assembly. By that time, high-vacuum pumps and vacuum gauges had been commercially produced in the country.

The new accelerator has already been assembled in the new building 'B'. The electromagnet was installed on the first floor, and the 150-Hz power supply unit (also a new one) in the vault below, together with capacitor batteries making a resonance circuit with the secondary winding of the electromagnet. All systems were successfully tested in late 1947. The accelerator was for the first time run in the betatron mode on 28 December 1947. The very first applying of voltage to the injector by B L Belousov produced an electron beam recorded by Geiger counters placed around the hall. All witnesses to the success rushed to lift up VI. By 11 January 1948, the accelerator was operated in the synchrotron mode with the following design parameters [5]:

Maximum magnetic field H	4200 Oe
Electron stationary orbit R	21.6 cm
Accelerating electric field frequency	216 MHz
Beam pulse duration t	1 – 2 μs
Intensity	10^6 electrons s^{-1}
Electron energy	30 MeV

One of the creators of the synchrotron, B S Ratner, recalled the role of V I [6]: "V I Veksler was the life and soul of the accelerator construction team. Within a short time, he managed to form a small but hard-working group, instill his ideas in the minds of people, and successfully resolve the complicated problem that required the joint efforts of physicists (both experimenters and theorists), engineers, technicians, and workers. V I Veksler encouraged initiative and independence in his subordinates. He was not petty-meddling supervisor; he just kept an all-seeing eye on the performance of each team member, thus maintaining high efficiency of collective work. People were busy from morning till late in the evening. The situation in the laboratory was quiet, free from the fuss and nervousness that frequently accompany such rushed work. B L Belousov was the closest associate of V I Veksler; his group bore direct responsibility for assembling and commissioning the synchrotron."

Participants in the work included A Ya Belyak, K I Blinov, L N Borodovskaya, S S Borodin, E L Burshtein, B B Gal'perin, V I Dragan-Sushchev, F M Elizarov, Yu S Ivanov, I D Kedrov, A A Kolomenskii, A P Komar, N G Kotel'nikov, D D Krasil'nikov, V G Larionova, A V Makarov, E A Man'kin, E M Moroz, A A Nikolaev, V E Pisarev, A V Porosyatnikov, M S Rabinovich, B S Ratner, I O Stal', G M Strakhovskii, P A Cherenkov, K V Chekhlov, V E Yakushkin, and workers from mechanical, glass-blowing, and instrument shops [6]. (Some 30 years later, the magnet of the synchrotron was moved to the Polytechnical Museum, Moscow.)

The report on the development and commissioning of the S-3 synchrotron was compiled in 1949 under the heading "Report on the facility." The code name S-3 was crossed out by the supervising First Department. Physical studies performed at the synchrotron will be described below.

While the construction of the synchrotron was underway, experimental confirmation of the principle of phase stability was reported. A synchrotron converted from a betatron was commissioned in the UK, and a 70-MeV synchrotron in the United States. This gave rise to a competition, and V I resolved not to miss his chance. The development and fabrication of components for a more powerful accelerator with an energy ten times that of the S-3 synchrotron started at the Etalon Laboratory concomitantly with the work on the previous machine. The results were published in two FIAN reports for 1947: "Physical substantiation of the design order on a powerful resonance accelerator (synchrotron)", and "Rationale for the choice of electromagnet design for the S-facility. Specifications for the S-facility electromagnet model."

At that time, Kaluzhskaya zastava (presently the Gagarin square) formed part of the Moscow city boundary that ran along the circular railway separating Moscow from the surrounding countryside with its villages, fields, and meadows. A thermoelectric power station, TETs-20, was built on the outside of the railway, opposite the Botanical Garden nursery famous for its rose garden. A narrow dirty passage between the power station and the nursery terminated in a vast dump site along the small Chura River. The passage was called Svalochnoe (Dump) shosse. V I chose the place for the new accelerator in the vicinity of TETs-20 as a powerful source of electricity. Its address read as follows: Svalochnoe sh., 19A (and now — prosp. 60-letiya Oktyabrya, 7A). The new building for the accelerator was built in 1947 – 1948. It was called Pitomnik (Nursery) for secrecy. The 250-MeV electron synchrotron S-25 was commissioned in this building in 1949. It was used for the first studies of photomeson interactions, Compton scattering, etc.

A 500-MeV proton synchrocyclotron converted from a cyclotron based on the phase stability principle was commissioned at approximately the same time in Dubna. In late 1948, V I Veksler, A A Kolomenskii, V A Petukhov, and M S Rabinovich issued a FIAN report entitled "Physical grounds for projecting a 10-GeV synchrophasotron of the USSR Academy of Sciences." Soon after that, theorists and experimenters, including those from the Research Institute of Electrophysical Equipment (Leningrad), FIAN Laboratory No. 11 headed by A L Mints, and other institutions started to design a 10-GeV synchrophasotron. Simultaneously, its 180-MeV model (under the code name 'MKM project') was constructed at FIAN to try out technical solutions to the anticipated start-up problems. The big machine having been commissioned, this accelerator was upgraded to become an electron synchrotron.

I V Veksler was the scientific leader and ideologist of the project. It was decided to locate the synchrophasotron in Dubna as well, near the Ivan'kovskaya hydroelectric power station on the Volga River. The technical directorate of the construction works (TDS-533) was established in early 1952. The Electrophysical Laboratory of the USSR Academy of Sciences (EPLAN) was organized soon after. I V Veksler was taken on to the staff of EPLAN on 26 October 1954 by the decision of the Presidium of the USSR Academy of Sciences but maintained a part-time position as the head of the Etalon Laboratory. Actually, he simultaneously and with equal efficiency worked at FIAN, Moscow State University, and EPLAN.

Creating such a unique complex required the coordinated activity of many organizations (design offices, research institutes, industry). The railway side-line linking Verbilki and Dubna, a 140-MW power substation, buildings for conducting physics experiments and for power supply facilities were constructed in a very short period, and a huge foundation pit was excavated. In 1955 – 1956, the magnet, different units of the accelerator, and its controlling and measuring instrumentation were assembled. The work had to be done in a very short time. Problems were many, and it was Veksler's energy that helped to quickly solve them.

Pre-commissioning work started at the beginning of 1957. On March 15, 1957 (while S K Esin, later head of construction of the high-current proton accelerator, the so-called Meson Factory of INR, Troitsk, was on duty), L P Zinov'ev obtained the 'betatron regime' at which protons sent from the injector continued to orbit in the absence of an accelerating field. In one month (15 April 1957), feeding rated current (12,500 A) to electromagnet windings yielded accelerated protons with an energy of 10 GeV. The highest-energy accelerator in the world came into regular operation. Several modifications to the injector allowed beam intensity to be increased by almost three orders of magnitude. The discovery of a new particle, the antisigma-minus hyperon, was first reported in 1960; it was followed by publications on D-resonance and other previously unknown phenomena.

In 1956, the Joint Institute for Nuclear Research (JINR) was established in Dubna with EPLAN as the base. V I Veksler became director of the Laboratory of High Energies (LHE) focused on elementary particle physics. The staggering achievements of V I became possible due to his scientific intuition and engineering talent. Over many years, he assembled instruments and machines he invented, doing much of the rough work himself. He was a born organizer able to inspire and motivate co-workers into following him [3]. In 1958, V I Veksler was elected Full Member of the USSR Academy of Sciences, and in 1963 he filled the position of Academician-Secretary of its newly established Division of Nuclear Physics. Here again he made a vital contribution to the further development of this discipline.

Simultaneously, V I continued research at FIAN and its 'Pitomnik' branch, where the left wing of the building (nearer to the entrance-gate office) was completed in 1956. The S-3 synchrotron ('number three' in the laboratory vernacular) was transported to this building across the territory of the still existing nursery under the supervision of Chief Engineer V N Logunov. Several university undergraduates, namely Yu Goncharov (scientific adviser B S Ratner, photoprotons), B Dolbilkin (scientific adviser O V Bogdankevich, inelastic photon scattering by indium and silver nuclei), Yu Melikov (scientific adviser E P Ovchinnikov, upgrading S-3 parameters), who had been receiving practical training in Veksler's laboratory beginning in 1954, acted as 'physical' manpower ("worked according to speciality" as physicists commented in jest). Later on, the remaining staff of Veksler's laboratory doing research at S-3 also moved to Pitomnik from the old building. Some researchers engaged in electron plasma physics and cooperative methods of an acceleration had been working in the new FIAN building (Leninsky prospekt) as from 1951. The synchrotron was installed in the cellar and started operating again a short time later, so that its beam was used to resume studies that laid a basis for the nuclear physics of electromagnetic interactions in this country.

In 1948, B S Ratner, Yu K Szhenov, and V F Kozlov studied the S-3 bremsstrahlung spectrum (progress report from FIAN, 1949). The theoretical Bethe – Heitler cross section was not experimentally verified at that time. Photon energy was measured by registering electron – positron pairs produced by photon in a target with large Z. A vacuum chamber with the target and two hand-made Geiger counters were positioned in the constant-field magnet gap. The observed spectrum turned out to be consistent with the predicted one within the measuring error; this provided the possibility of determining cross sections of photonuclear reactions in subsequent studies. The bremsstrahlung spectrum of S-3 photons was measured more accurately in a later study (1962) [7].

In the old FIAN building (Miusskaya str.), V I occupied a room adjoining room No. 16 where S-3 accelerator was located. V I did not frequently drop in there after the advent of S-25 synchrotron but always showed interest in S-3-based studies, ready to give helpful advice. Indeed, he could be seen only occasionally after the S-3 team moved to Pitomnik, and especially when he started to constantly work in Dubna. Nevertheless, V I continued to lead investigations carried out at FIAN on his initiative, giving a great deal of attention to cooperative methods of an acceleration. Also, he was a most active participant at seminars held in the laboratory. Things stood like this till 1959 when the USSR Council of Ministers adopted the resolution "On combined job limitations."

The laboratory of Photonuclear Reactions was officially established at FIAN on 1 December 1959. Three weeks earlier, director of FIAN Academician D V Skobel'tsyn issued an order dividing the laboratory headed by VI; its abridged text is given below [2]:

Order No. 369
P N Lebedev Physical Institute, USSR Academy of Sciences
Moscow November 9, 1959

1. In pursuance of the decision of the Institute's Scientific Council, the Laboratory of Accelerators and Photonuclear Reactions is to be divided as of December 1 into three independent laboratories and placed directly under the authority of the administration of the institute:

(a) The Laboratory of Accelerators (head V I Veksler, Full Member of the USSR Academy of Sciences; deputy head and head of a sector M S Rabinovich, D. Phys.-Math. Sci.; chief engineer M G Sedov; deputy head of administrative management Leman).

(b) The Laboratory of Photomeson Processes (acting head and head of a sector P A Cherenkov, D. Phys.-Math. Sci.; deputy head A N Gorbunov, Cand. Phys.-Math. Sci., junior researcher; deputy head of administrative management S A Pokrovskii).

(c) The Laboratory of Photonuclear Reactions (acting head L E Lazareva, senior researcher; chief engineer V N Logunov).

The decision being approved by the USSR Academy of Sciences Presidium, the competition for filling two vacancies of heads of laboratories will be announced.

2. The scientific secretary of the Institute, Professor N N Sobolev, and head of the Staff Department, P G Trofimenko, should prepare within one week all the materials for the reorganization of the Laboratory of Accelerators and Photonuclear Reactions to be submitted to the Division of Physical-Mathematical Sciences, USSR Academy of Sciences.

Signed: D V Skobel'tsyn, Full Member of the USSR Academy of Sciences, Director of FIAN

However, a new order [2] from the Director of FIAN was issued within three months after passing the aforementioned governmental resolution. Paragraph 3 of the order read: "Academician I V Veksler is released from his duties as the head of Laboratory of Accelerators as of 15 February 1960." Somewhat later, therefore, the Laboratory was divided into the Laboratory of Accelerators proper (head A A Kolomenskii), the Laboratory of Plasma Physics (head M S Rabinovich), and the Laboratory of the S-68 Synchrotron [constructed in the early 1950s as a prototype proton synchrophasotron (MKM project), head V A Petukhov]. Once commissioned, this facility was upgraded to electron accelerator with a maximum energy of 680 MeV (the so-called 'Sklad-2').

Thus, the laboratory founded by V I Veksler (and called the Etalon Laboratory after the nuclear physics laboratories of FIAN were incorporated into the Soviet atomic project) gave rise to five independent laboratories. Moreover, V I was constantly busy organizing studies in the Laboratory of Cosmic Rays and similar investigations in the Laboratory of Atomic Nucleus (LAN) where he had been deputy director responsible for the work of the Elbrus and Pamirs expeditions from 1938. The life of V I was inseparable from the unprecedented rapid advance of nuclear physics in this country. If only a dozen of scientists were engaged in nuclear physics research in 1936, these studies in the 1960s involved large institutes and other organizations. Facilities for experiments in high-energy physics became huge in size and much more complicated in design than their forerunners. New industries were created for their construction in the USSR. In 1963, the USSR Academy of Sciences established the Division of Nuclear Physics, headed by V I Veksler. Such is the brief prehistory of appearing the Laboratory of Photonuclear Reactions (LPNR) at FIAN.

V I Veksler, head of the Laboratory of Cosmic Rays, and L E Lazareva, junior researcher, participating in a seminar (1945).

3. Laboratory of Photonuclear Reactions, FIAN (USSR AS INR since 1971)

Lyubov' Efremovna Lazareva was at the head of LPNR from 1960 till 1986. Her scientific biography before then was briefly as follows:

— joined FIAN as an undergraduate of the Department of Physics, Moscow State University (1936);

— joined the staff of FIAN (1937);

— participated in the Pamirs Expedition headed by V I (Chechekty, autumn 1944). She registered heavy particles in cosmic rays with proportional counters jointly with Veksler's postgraduate students L Bell and N Birger. They observed showers consisting of large number of high-energy particles passing through a 6-cm thick lead plate;

— defended her thesis "Atmospheric showers of cosmic rays at an altitude of 3,860 m above sea level" for the Candidate of Sciences under the supervision of D V Skobel'tsyn and I V Veksler (late 1945).

The S-3 accelerator remained the main instrument of physical research at LPNR for 40 years. Its beam was used for in-depth studies of photonuclear reactions in the giant dipole resonance (GDR) region. The main avenues of experiment included:

— proton- and neutron-emitting reactions;

— photofission;

— inelastic scattering of photons;

— absorption cross sections by light and medium nuclei, GDR fine structure;

— absorption cross sections by heavy nuclei, nuclear deformation.

B S Ratner pioneered photoproton reaction studies at S-3 synchrotron (together with E M Leikin and R M Osokina). In 1954, he defended his thesis "A study of the (γ, p) reaction induced by quanta with an energy of up to 30 MeV" for Candidate of Sciences. This work was based on the results of investigations into energy and angular distributions of protons emitted by Al, Cu, Ni, and Pb nuclei; it demonstrated a new decay mechanism other than the statistical one. Its characteristic feature was the strong dependence of the fast proton fraction in the Cu nucleus on variations of the maximum photon energy in the spectrum, probably reflecting the nuclear shell structure. The cross section of the Cu(γ, p) reaction for protons with an energy higher than 5 MeV was shown to have three resonances with roughly equal amplitudes [8] (Fig. 1). In addition, fast neutron emission cross sections for nuclei with $A \sim 60$ were measured to obtain an insight into the decay of the doorway states of these nuclei in the GDR region. Neutrons with an energy of $\varepsilon_n \geqslant 3.7$ MeV were detected with a high-performance stilben spectrometer based on recoil proton analysis. It was revealed that the cross section structure of high-energy neutrons in the reaction ^{58}Ni(γ, n) was on the whole analogous to the total cross section of this reaction. However, the two maxima in the 21 – 23 MeV region were shifted by ~ 1 MeV. Measurements at the maximum photon energy of 19.0 MeV demonstrated an equilibrium photoneutron spectrum suggesting the decay for $E < 19$ MeV only into more complex states [8].

An important factor determining the reliability of the results was the stability of the upper edge of the bremsstrahlung spectrum. The work on its stabilization was initiated by the group led by O V Bogdankevich, and continued by the group of B S Ratner. The error in the measurement of $E_{\gamma\,\max}$

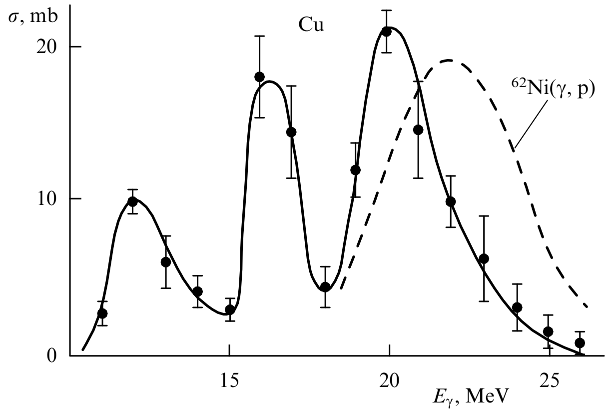


Figure 1. Cross section of the Cu(γ, p) reaction for protons with energies exceeding 5 MeV [8].

was eventually reduced to ±1.5 keV, and absolute energy scale calibration was 10 keV. These parameters made it possible to measure the GDR fine structure near (γ, p)-reaction thresholds on ^{53}Cr, ^{62,64}Ni nuclei [9] and continue studying nuclear doorway states during GDR formation. In the course of work, data reliability was further improved by automation of experiments with Elektronika-60 and SM-4 computers for measuring the set of yield curves and maintaining spectrum stability.

Direct measurements of the total photoabsorption cross section for light nuclei to elucidate the giant-resonance fine structure were made by the attenuation method for the first time in the world. At that time, the structure of total cross sections of photon – nucleus interactions was not established experimentally; only global parameters of GDR were known. The reliable registering required apparatus with a high-energy resolution. A magnetic pair spectrometer was designed at LPNR for this purpose. The magnetic field in the workspace 40 cm in diameter remained uniform to within 0.05% as maintained by NMR with an accuracy of 0.01%. A radiator (gold foil as thick as 10 mg cm^{-2}) was placed inside the vacuum chamber, and the bremsstrahlung-spectrum photons were incident on the radiator after attenuation. A system of coincidence and anticoincidence scintillation counters was installed behind the slots 0 – 6 mm wide limiting the solid angle. With slots of widths 2 and 4 mm, the energy resolution at 20 MeV was 100 and ~ 200 keV, respectively. Systematic errors were diminished by alternate measurements of the N_0/N ratio (the number of true coincidences in the absence and presence of an absorber in the beam). The nuclear cross section was found by subtracting cross sections of atomic processes with additional normalization below the partial reaction threshold from the total cross section of photon interactions. Statistical precision was enhanced by the use (since 1962) of a nine-channel pair spectrometer with an efficiency almost 10 times that of the earlier apparatus. For the same purpose, some measurements were made at S-25 synchrotron; photon intensity in the GDR region turned out to be several-fold higher than at S-3. (This method is described at length in Refs [10, 11].)

Photon absorption cross sections were measured in the GDR region for the following nuclei [10 – 12]:

$$^{9}\mathrm{Be},\ ^{12}\mathrm{C},\ ^{16}\mathrm{O},\ ^{19}\mathrm{F},\ ^{\mathrm{nat}}\mathrm{Mg},\ ^{27}\mathrm{Al},\ ^{32}\mathrm{S},\ ^{40}\mathrm{Ca},\ ^{55}\mathrm{Mn},\ ^{56}\mathrm{Fe}\,.$$

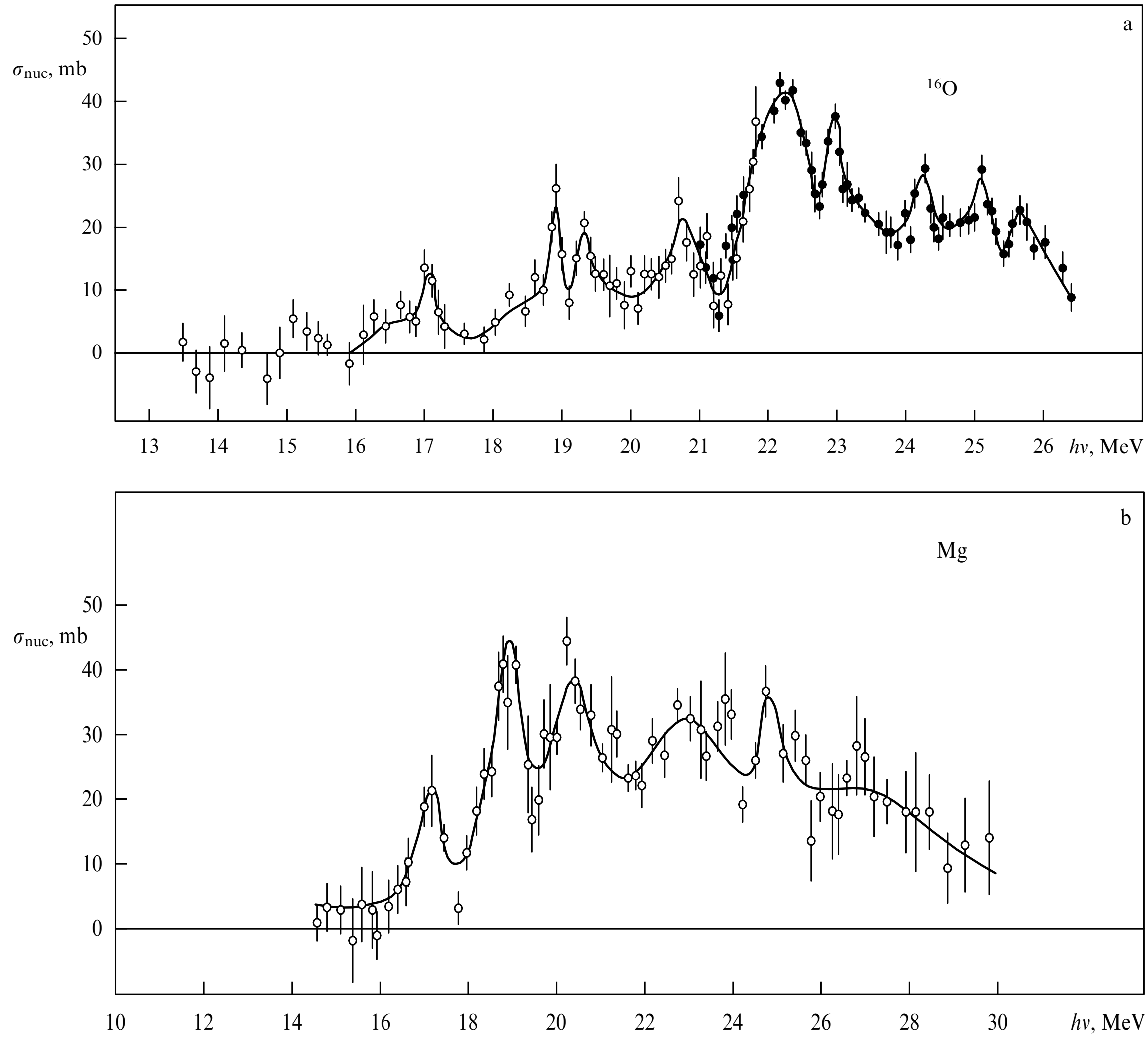


Figure 2. (a) Cross section of γ-quanta absorption by the ^{16}O nucleus in the GDR region [10]. (b) Cross section of photon absorption by the Mg nucleus in the GDR region [11].

The doubly magic ^{16}O nucleus was measured with a higher accuracy and better energy resolution ($\leqslant 0.5\%$) [10]. Nine resonances were distinguished in its absorption cross section within the 13.5 – 27.0-MeV range (Fig. 2a). The lower three resonances (17.2, 19.0, 19.4 MeV) were located on the low-energy slope of GDR; they accounted for 14% of its intensity.

The integrated cross section in the above range amounted to 170 ± 20 MeV mb or 50% of the value given by the Thomas – Reiche – Kuhn sum rule. Calculations of GDR in the ^{16}O nucleus predicted 5 resonances with 67 – 74% of intensity concentrating in the 22.3 ± 0.2 MeV maximum, in conflict with experimental data. The better agreement was achieved when calculations took into account the admixture of higher configurations. They predicted 6 resonances, five of which were close to the experimentally established ones in terms of distribution; however, theoretical intensity (1%) in the first resonance at 18 MeV proved much lower than for the measured cross section (14%) [10].

The practically complete structural coincidence of the absorption cross section and the cross sections of main partial reactions (γ, p) and (γ, n) may be regarded as a manifestation of the charge symmetry of nuclear forces.

Results of measuring the cross section of photon absorption by the ^{16}O nucleus and its structure were recognized as a classical study of photonuclear reactions. (They are cited and discussed in the monograph *Nuclear Structure* by A Bohr and B Mottelson.)

Measurement of the nuclear absorption cross section from the next sd-shell is exemplified by an experiment with ^{nat}Mg. In the 15.0 – 30.0 MeV excitation energy range, the Mg cross section showed 6 resonances, with the average cross section being almost invariably constant within a range of 19 – 26 MeV (Fig. 2b), while calculations predicted two groups of transitions (K = 0 and 1) with maximum values at 17 – 18 and 22 – 25 MeV [11].

Also examined was the cross section structure of γ-quanta absorption by the ^{32}S nucleus with closed $1d_{5/2}$ and $2s_{1/2}$ subshells [12]. The main GDR maximum was found at 19.6 MeV; it corresponded to 38% of the integrated cross section over the measured interval. Resonances in the total cross section repeated in partial reactions (γ, n) and (γ, p_0).

Comparison of the strongly structured experimental cross section (Fig. 3a) with two variants calculated from shell models (Fig. 3b, c) suggests fairly good agreement between them [12]. The theoretical approach predicts GDR splitting for the ^{32}S nucleus in accordance with transitions from unfilled ($1d-2s \rightarrow 1f-2p$) and filled ($1p \rightarrow 1d-2s$) shells. Resonances in the 16.5 – 18.5 MeV region correspond to the

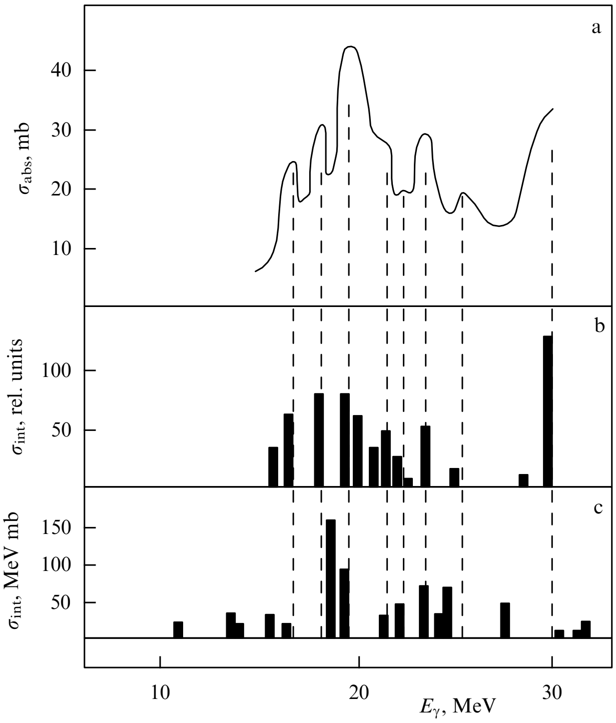


Figure 3. Comparison of experimental (a) and theoretical (b, c) cross sections of γ-quanta absorption by the ^{32}S nucleus [12].

former group, and resonances at higher energies to the latter one. The collection of total cross sections taken over light nuclei provides the possibility of verifying different model approaches to GDR computations, including splitting of GDR in the nuclei with (1d – 2s) and (1f – 2p) shells.

In subsequent years, the absorption method was employed to measure total cross sections of photoabsorption by heavy nuclei for which the nuclear part of the cross section did not exceed 1% of that measured for the summary (atomic + nuclear) cross section. The necessity of high statistical precision (better than 0.1%) of measurements dictated by the smallness of the nuclear constituent of the cross section required using a special spectrometer with recording efficiency close to 100%. To this end, a full-absorption scintillation spectrometer was designed based on a large NaJ(Tl) crystal; it was used in two series of numerous measurements on lanthanide and actinide nuclei (a total of 18 isotopes) [13, 14].

The influence of shell effects on GDR in nuclei was evaluated close to a deformed neutron subshell $N = 108$. The total photoabsorption cross sections thus obtained for nuclei in the $165 < A < 209$ range (Fig. 4) allowed to clarify the cause of the experimentally examined discrepancy between the behavior of the giant resonance width Γ and the nuclear deformation parameter β. Figure 4b clearly demonstrates the effect of filling the neutron subshell $N = 108$ on the giant resonance width [13]. Results of the still unique measurements on a group of actinide nuclei suggest the similarity of 'transition' effects observed on nuclei with the number of neutrons and protons close to the magic number 90; it confirms the validity of the principle of charge independence of nuclear forces [14].

The data obtained on total photoabsorption cross sections of heavy nuclei provided important material for the

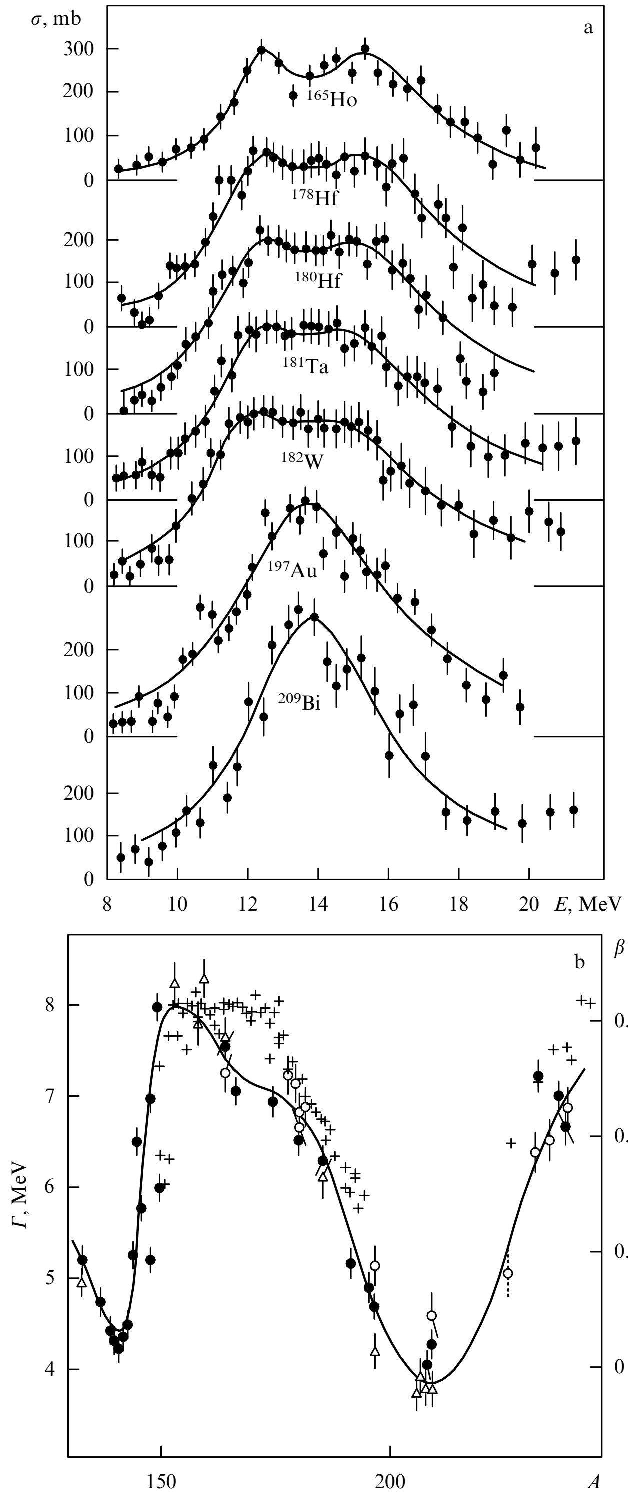


Figure 4. Total cross sections of γ-quanta absorption by nuclei with $165 \leqslant A \leqslant 209$ (a) and the difference between the giant resonance width Γ and the nuclear deformation parameter $\beta = (E_2 - E_1)/A^{1/3}$ near the filled neutron shell $N = 108$ (b) [13].

verification of various collective nuclear models, including $\sigma^{int}/\Sigma^{TRK}$ ratio constancy for nuclei with $232 \leqslant A \leqslant 239$.

Photofission cross sections of transuranium ^{241}Am and ^{243}Am nuclei were for the first time measured at the S-3 synchrotron in the GDR region; neutron and fission widths for these nuclei were also determined [15]. During a long period of measurements, the determination accuracy and

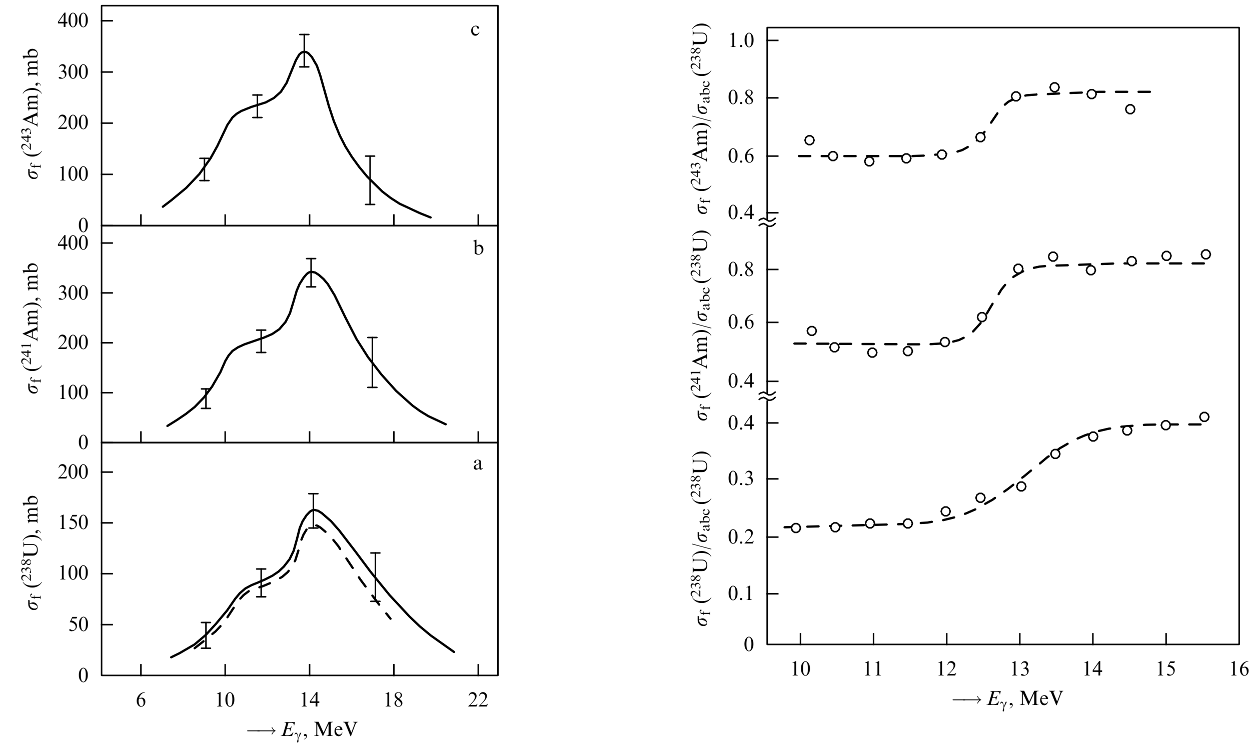
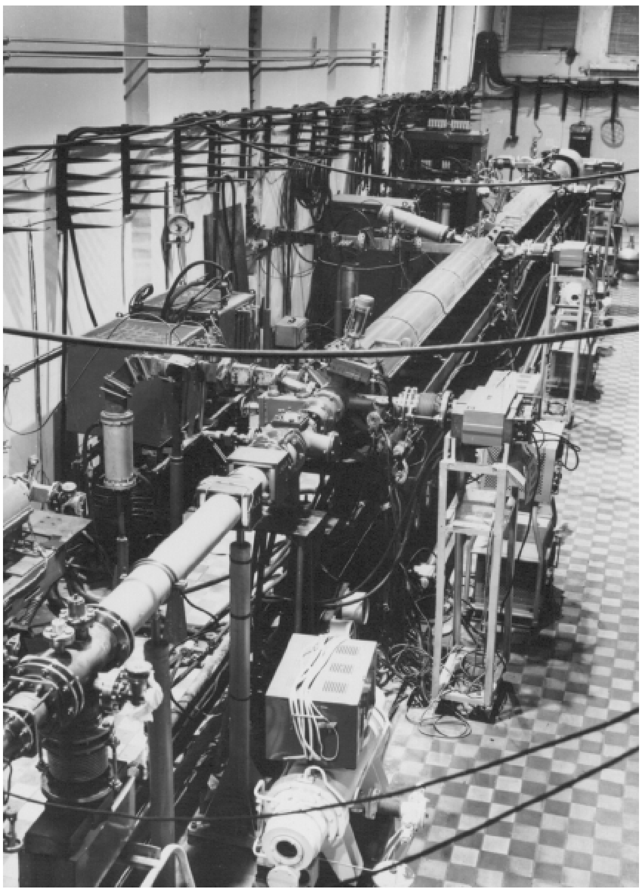


Figure 5. Photofission cross sections of ^{238}U (a), ^{241}Am (b), and ^{243}Am (c) nuclei as functions of photon energy. Plots on the right: fission-to-total photoabsorption (fissionability) cross section ratios for these nuclei [15].



LPNR 50-MeV electron linear accelerator (upgraded to 100-MeV LUE-100).

stability of the energy of electrons accelerated in the synchrotron were no worse than ± 10 keV. Fission fragments were registered in spark corona-discharge chambers. Results of the measurements are presented in Fig. 5, whence it is obvious that fissionabilities are constant within the measurement error ($\pm 8\%$) in an energy range from ~ 8 MeV up to the (γ, nf)-reaction threshold roughly equaling 12.5 MeV; they behave similarly for all the nuclei studied. The resulting yield ratios give the following fissionability values: ^{241}Am — 0.53 ± 0.03, ^{243}Am — $0.61 + 0.04$. These data are at variance with the predictions of the liquid drop model and suggest a complex (two-hump) structure of the barrier.

Development of accelerators remained the highest priority for V I Veksler. In 1963, with his support the decision was taken to build two new accelerators. One was the 1.3-GeV synchrotron S-25R in the Photomeson Laboratory of FIAN, Troitsk, commissioned in 1972 (a large territory outside the town was chosen pending the construction of one more higher-energy accelerator). The other was the 50-MeV linear electron accelerator located in the LPNR basement for which an addition to the main Pitomnik's building has been constructed. It came into operation in 1970; later on (1978), its energy was increased to 100 MeV.

The accelerator was brought into operation when LPNR was incorporated into the USSR Academy of Sciences Institute of Nuclear Research (INR), organized in 1971. New research groups were formed to study the scattering of electrons and quasimonochromatic annihilation photons. For several years, these small groups created complex systems of up-to-date instruments for the investigation of electron- and photon-nuclear reactions. A unique up-to-date facility for electron scattering experiments was designed and constructed [16]. Its basic element was a magnetic spectrometer with a 'magic angle', having an intrinsic resolving power of $\sim 10^{-4}$ and stability of $\sim 10^{-5}$. An electron beam was guided onto the target by an original three-magnet achromatic transportation system ensuring an electron energy resolution of 10^{-3}. The overall resolving power of the facility was $\sim 2 \times 10^{-3}$. Electron scattering experiments provided data for the determination of charge distribution on the ^{12}C nucleus, and parameters of the ground and lower-excited states of the ^{27}Al nucleus.

Another system of beam transportation was designed and tuned for experiments with positron annihilation γ-quanta. It was used to measure the cross section of the $^{63}Cu(\gamma, n)$ reaction in the 12 – 25-MeV energy range [17].

Scientists at LPNR carried out extensive theoretical studies (B A Tulupov, R A Eramzhyan). When L E Lazareva reached retiring age, LPNR was headed by R A Eramzhyan (till 1998) and thereafter by V G Nedorezov. The S-3 and LUE-100 accelerators were decommissioned in the early 1990s.

The quantity and quality of scientific results amassed at LPNR originating from Veksler's Laboratory of Accelerators and Photonuclear Reactions pushed it to the forefront of research on nuclear electromagnetic interactions in energy ranges attainable at the S-3, LUE-100, and partly S-25 accelerators. Many LPNR studies received world-wide attention and were recognized as classical studies.

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Synchrophasotron studies

V A Nikitin

1. Introduction

The outstanding Soviet scientist V I Veksler combined the talents of brilliant researcher and organizer. In the difficult post-war years, he was at the head of a challenging project aimed at the creation of the then largest accelerator in the world, the synchrophasotron. The synchrophasotron gave birth to many fundamental discoveries and was the basis of pioneering studies in high-energy physics, such as the elucidation of decay properties of K-mesons and vector mesons, measurements of total and differential cross sections of proton interactions with pions, protons, and K-mesons, and production of nuclear beams, including polarized deuterons. Above all, synchrophasotron studies laid the foundation for relativistic nuclear physics at large and greatly promoted extensive international cooperation of scientists. The development of experimental techniques contributed to progress in related disciplines and applied studies.

2. V I Veksler's ageless legacy

This year (2007), the scientific community celebrates the 100th anniversary of the birth of the prominent Soviet scientist Vladimir Iosifovich Veksler. He is known to physicists all over the world as the author of one of the most important discoveries of the 20th century, the principle of phase stability, which underlies all currently operating cyclic accelerators of relativistic particles. In the difficult post-war years, Veksler was the leader of an ambitious project for the creation of the then largest accelerator in the world, the synchrophasotron (SP), in the city of Dubna. The project was carried out at the P N Lebedev Physical Institute, USSR Academy of Sciences and approved by its director D V Skobel'tsyn in January 1951. Veksler shared responsibility for project implementation with A P Komar, M A Markov, V A Petukhov, M S Rabinovich, A A Kolomenskii, and K I Blinov. The program of physics research was prepared by M A Markov, I V Chuvilo, V I Gol'danskii, A A Kolomenskii, A N Gorbunov, and A E Chudakov in 1952. The creators formulated the main tasks as the investigation of the multiparticle production in proton – proton collisions, the measurement of elastic and total cross sections of the π-meson interaction with protons, and the search for new particles, in particular, antiprotons. They also anticipated the formation of nuclear matter composed of pions. The world-record proton beam energy of 10 GeV was achieved at SP in March 1957. The Laboratory of High Energies (LHE), headed by Veksler, was incorporated into the Joint Institute for Nuclear Research (JINR) and became an arena of broad international scientific collaboration. The commissioning of the SP had world-wide resonance as an outstanding achievement in nuclear physics. The world press described it as "the world's eighth wonder." Niels Bohr, when he visited JINR in 1961, pronounced a well-turned and faithful phrase: "He who invented and constructed such a machine had to be a very brave man."