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 $^{63}\mathrm{Cu}(\gamma, n)$ 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."

Investigations at the SP brought about a number of fundamental discoveries in high-energy physics, while the development of experimental techniques greatly promoted progress in neighboring fields of science and applied research. V I Veksler had versatile talents as a scientist and organizer. His never-aging scientific heritage covers a variety of aspects of accelerator and experimental physics. He founded and led a school of scientists and engineers who continue developing his ideas in many laboratories all over the world [1].

3. First turns of the accelerator beam

The team of scientists that eventually constituted the staff of the Laboratory of High Energies in Dubna formed in 1953 – 1955. The development of relevant methodical issues started at about the same time. The program of physical research began to be implemented as soon as the 10-GeV proton beam was produced. Listed below are the most important studies carried out over the initial period (1957 – 1965) and the names of principal investigators. Almost all this work was successfully continued on the U-70 accelerator of the Institute for High-Energy Physics (IHEP) and higher-energy accelerators:

V I Veksler, I N Semenyushkin, A B Kuznetsov — generation of an antiproton beam by the high-frequency separation technique [2];

A L Lyubimov, L N Strunov — generation of a tagged antiproton beam and registering of antihyperons in the Wilson chamber;

A L Lyubimov — measurement of total and differential cross sections of πp scattering [3];

A S Vovenko, B A Kulakov, M F Likhachev, Yu A Matulenko, I A Savin, V S Stavinskii — development and construction of Cherenkov gas counters [4];

E O Okonov, D Nyagu, V A Rusakov — studies of K^0-meson decays, the search for the K^0-meson antigravitation effect [5]. Observation of $K_2^0 \rightarrow K_1^0$ regeneration and verification of the Pomeranchuk theorem [6];

M I Solov'ev, G M Stashkov, N M Viryasov, R M Lebedev — construction of bubble chambers and a program of research with the use of them;

M I Podgoretskii, K D Tolstov, V V Glagolev, I M Gramenitskii, V I Lyubimov, V A Nikitin, M G Shafranova — irradiation of emulsions and an extended program of relevant research [8];

V I Moroz, M N Khachaturyan, I V Chuvilo — formation of a neutron beam and measurement of total np-interaction cross sections;

M N Khachaturyan, A M Baldin, M A Azimov — construction of a Cherenkov γ-spectrometer and observation of vector meson decays into e^+e^--pairs [9];

V A Sviridov, V A Nikitin, L N Strunov — small-angle elastic scattering of particles [10];

K D Tolstov, V A Nikitin, L S Zolin, Yu K Pilipenko — construction of a supersonic gas jet target [11].

Left to right: Niels Bohr, I E Tamm, and V I Veksler in Dubna (1961).

4. Studies with bubble chambers

In the 1950s – 1960s, bubble chambers were an important tool for studying particle interactions. These facilities provide a number of important advantages, such as the possibility of being filled with various substances (hydrogen, propane, xenon, etc.) serving as both targets and sensitive media, large particle registration volume (up to several cubic meters), high-precision measurement of point coordinates at the tracks (~ 200 μm), and the possibility of recording γ-quanta (especially in xenon chambers) and observing interactions over the full solid angle 4π, etc. Several gas and bubble chambers were constructed at JINR LHE in 1955 – 1970, including Wilson chambers (gaseous hydrogen, helium, argon) 40 cm, 50 cm, and 1 m in size along the beam; propane bubble chambers (24.1 l and 2 m); a xenon bubble chamber (50 cm); hydrogen bubble chambers (40 cm, 1 m, 2 m), and a hydrogen chamber (2 m) with a deuterium target [7].

Selected results of bubble chamber studies are briefly expounded on below. They were obtained with the SP at beam energies of 3 – 10 GeV and with the U-70 accelerator (IHEP) at proton and pion energies of 70 and 40 GeV, respectively [12].

The inertial properties of barion charges were discovered: the angular distribution of barions in the center-of-mass system was sharply anisotropic in pp- and πp-interaction events with pion multiplicity $n_\pi \leqslant 4$. Barions formed two cones, forward and backward, for pp-interaction. These particles were called 'leading', their momenta being much larger than the average momentum of the particles involved in this event. In πp-collision events, barions formed only one (backward) cone. Angular isotropy was observed in events with $n_\pi \geqslant 8$. The notion of a target and beam fragmentation region was introduced for forward – backward cones. The remaining part of the event was called the pionization region. It was later referred to as the central region.

Hydrogen bubble chamber of size 2 m on the assembly bench.

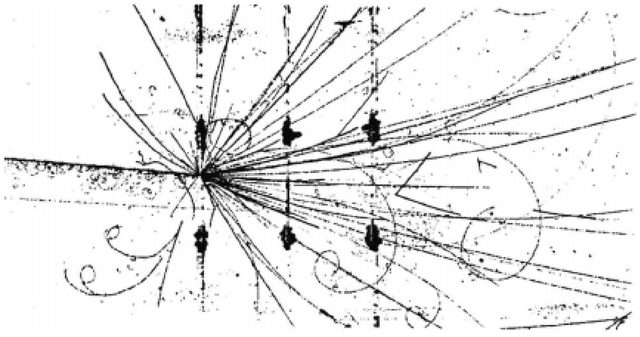

Figure 1. CT1-interaction event at a C-nucleus beam energy of 4.5 A GeV. The shot was taken in a propane chamber (2 m) with tantalum plates as the targets.

The momentum correlation of identical and nonidentical particles and the spatio-temporal dimensions of the interaction region were measured. The collection of the data was consistent with the multiperipheral model of multiparticle production.

A wealth of data on nucleus – nucleus interactions was obtained (dC, CC, CT1, etc.). These data are still important for the development of theoretical models concerning AA-collisions. A characteristic event of AA-interaction is shown in Fig. 1.

Characteristics of strange particle, antiproton, and antihyperon productions were obtained. Multiple production of strange particles was observed. The resonances $f(980) \to 2K$, $f(600) \to 2\pi$ (σ-meson) were discovered [13, 14].

An antihyperon $\bar{\Sigma}^-$ production event in the 24 l propane chamber was observed for the first time in 1960. This event deserves special mention for its uniqueness. The chamber was irradiated by a 7-GeV π^--meson beam. Figure 2 shows a photograph of this event and its interpretation. Interestingly, four strange particles were observed here. It was the first experimental evidence of the multiple production of strange particles [16].

5. Investigation of cumulative processes

Analysis of experimental data on interactions of leptons, protons, and nuclei with photons and nuclei, gathered in the early 1970s, prompted the idea of scale invariance of inelastic processes. This term implies similarity of secondary hadron spectra for different energies of primary particles. It is otherwise referred to as self-similarity or scaling. In the quantum field theory, by self-similarity is meant independence of the asymptotic shape of the amplitudes of processes proceeding at a high energy and a large transferred momentum from dimensional parameters, including particle masses. The dependence on dimensionless (scaled) momentum variables is called scale invariance. J D Bjorken appears to have been the first to propose this law in application to deeply inelastic electron scattering on protons [17]. The theoretical prediction was confirmed in experiment. The differential cross section of ep-scattering $e + p \to e' + X$ in the region with $E_{\rm e} \gg m$ and $Q^2 \gg m^2$ was found to be independent neither of the primary electron energy $E_{\rm e}$ nor of the four-momentum $Q^2 = -q^2$ transferred by an electron to the system of secondary hadrons X. The cross section depends only on the scale variable $x_{\rm B} = Q^2/2m\nu$. Here, $\nu = E_{\rm e} - E'_{\rm e}$ is the energy transferred by an electron to a proton, and m is the proton mass; the denominator in this expression may be called a scale or similarity parameter. It turned out in the course of time that Bjorken's scaling is weakly violated, i.e., the cross section logarithmically depends on Q^2. This weak but essential effect is presently understood in the framework of quantum chromodynamics and is not discussed here. In deeply inelastic scattering, an electron is supposed to interact with a certain constituent of a proton, the parton. In the physical sense, variable $x_{\rm B}$ is a fraction of proton momentum carried by a given parton. Evidently, $x_{\rm B}$ varies in the range $0-1$ for ep-collision. In the case of a collision with a nucleus,

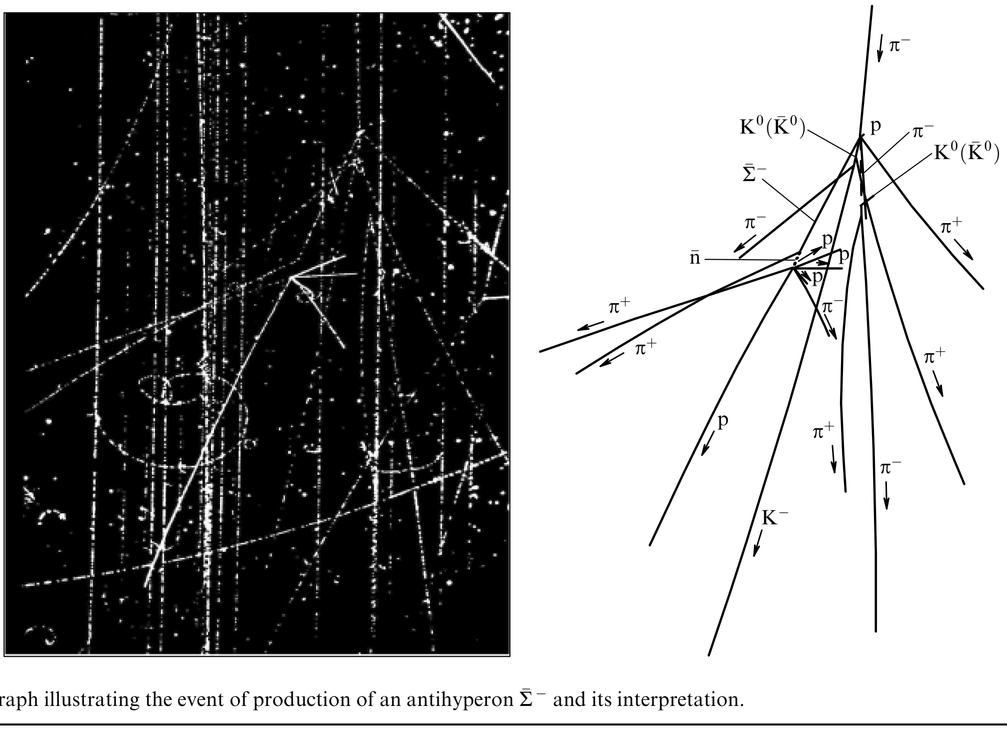

Figure 2. Photograph illustrating the event of production of an antihyperon $\bar{\Sigma}^-$ and its interpretation.

it is assumed that the electron may transfer the momentum to a group of nucleons (to be precise, to a parton belonging to a compact nucleon group). Then, a region of $x_{\rm B} \geqslant 1$ is conceivable as described below.

Analysis of experimental findings indicated that the cross section of an inclusive process $\mathrm{A + B \to c + X}$ (only one c particle is observable) can be conveniently represented by introducing the dimensionless scale variable $x = p_{\rm c}/p_{\rm c,\,max}$, where the scale parameter in the denominator is the kinematically feasible maximum momentum of particle c. Then, the cross section $\mathrm{d}\sigma/\mathrm{d}p_{\rm c}(s,\, p_{\rm c}) = f(x)$ is the universal function $f(x)$ independent of energy $\sqrt{s}$. In 1971, A M Baldin proposed a hypothesis [18] that cross sections of the $f(x)$ type in relativistic hadron interactions are determined by the local properties of hadron matter rather than by the geometric characteristics of objects A, B (e.g., form factors). In this case, the condition $E_{\rm A,B,c} \gg \varepsilon$, where ε is the characteristic binding energy of particles in objects A, B may be considered a criterion of 'relativism'. Hence the problem of relativistic description of excited hadron matter and lengthy composite objects. Thus, the era of relativistic nuclear physics began. Today, the totality of these problems is extensively being discussed in the context of the search for the quark – gluon plasma. However, such experiments cannot be confined by the inclusive approach. Plasma can manifest itself in the collective behavior of a large number of particles. For this reason, particles in each collision event should be recorded in a broad angular interval close to 4π.

A distinguished phenomenon in the sphere of these problems is a cumulative effect consisting in the fact that the energy of an inclusive particle in collisions of relativistic nuclei exceeds the energy per nucleon; to be precise, when a particle in the momentum space spreads beyond the boundary permitted by the kinematics of the collision of a pair of nucleons. The cumulative process can be described in terms of the excitation mechanism of a group of N nucleons: $\mathrm{N}^* \to \mathrm{c + N}$. The number N of nucleons depends on the nucleus (A or B), while the probability $P_N(\mathrm{N})$ of association of N nucleons has to be evaluated by a model, e.g., calculated based on the binomial law. Then, the cross section in the general form is given by the equation

$$E\,\frac{\mathrm{d}\sigma}{\mathrm{d}p} = \sum_{N_{\min}}^{A} P_N(\mathrm{N})\, f_N(x_N)\,. \tag{1}$$

The minimal number of nucleons in the association is defined by the kinematic relation

$$N_{\min} \approx E_{\rm c} - P_{\rm c}\,\frac{\cos\theta_{\rm c}}{m} \approx Q\,,$$

where $\theta_{\rm c}$ is the angle between momenta of particle c and the fragmenting nucleus. Quantity $N_{\min}$ is also denoted as Q and is called the cumulative number.

The first experimental verification of the cumulative effect hypothesis was reported by V S Stavinskii's group in 1971 [15, 18] using proton and deuteron beams accelerated in the SP up to a momentum of 10 GeV/c. The momentum of a single nucleon in deuteron was roughly 5 GeV/c. Cross sections of inclusive reactions

$$\mathrm{p + Cu \to \pi^- + X}, \quad \mathrm{d + Cu \to \pi^- + X}\,.$$

were measured. It turned out that the momentum spectrum of pions in the second reaction extends far beyond the boundary permitted by interaction kinematics for only a single nucleon pair. Also, the cross section ratio of the above reactions, $\sigma(\mathrm{d\,Cu})/\sigma(\mathrm{p\,Cu})$, was measured for values of the scale variable $x = p_{\pi}/p_{\pi,\,\max}$ in a range of $0.5 \leqslant x \leqslant 1$ at $p_{\perp} \approx 0$ and at different deuteron energies. These data are presented in Fig. 3. The solid curve exhibits the analytical approximation of nucleon – nucleon interaction data. Points denote pion yield in the d Cu reaction, magnified by a factor of 20 (for comparison). It can be seen that the cross sections of reactions d Cu and p Cu are similar, which confirms the validity of scale invariance in the kinematic region where the production of pions is feasible only in the case of joint action of a pair of nucleons in a deuteron. Figure 3b illustrates the behavior of the probability of a cumulative process, i.e., the quantity P_2 from Eqn (1). The value of P_2 can be assessed as the probability of finding two nucleons in a deuteron within a certain volume of radius $r \approx 0.7$ fm characteristic of meson formation: $P_2 = (r/r_{\rm D})^3 \approx 5 \times 10^{-2}$. Here, $r_{\rm D}$ is the deuteron radius computed from its wave function. The curves in this figure correspond to the calculated P_2 in the impulse approximation, the results of which are at variance with experimental data (by several orders of magnitude). Thus, the experiment confirmed the existence of a cumulative effect, the magnitude of which is consistent with the scale invariance hypothesis and a rather simple model of the combined action of two nucleons.

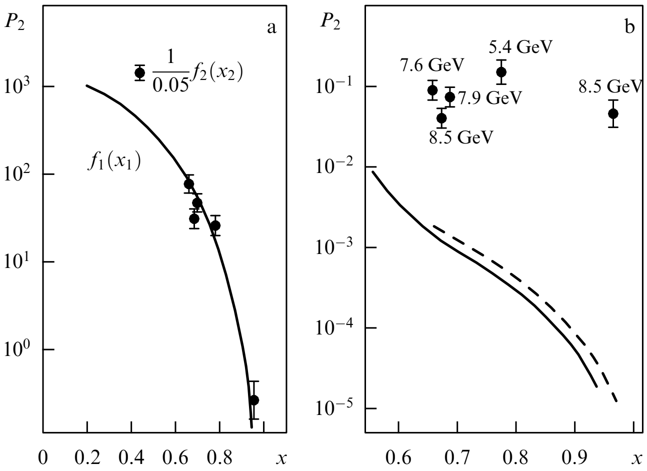

Figure 3. (a) Comparison of pion yields in reactions p Cu (solid curve) (f_1) and d Cu (●) (f_2). (b) Probability of the cumulative process P_2 in Eqn (1). The curves show the results of P_2 calculation in the impulse approximation.

The authors of Ref. [15] measured proton emission at an angle of 137° from a fragmenting carbon nucleus in the pC reaction at a proton energy in the 1 – 6 GeV range. The proton spectrum is presented in Fig. 4. Arrows show momenta that a proton quasielastically scattered on nucleon clusters of the d-, t-, and α-type must have as dictated by kinematics. Evidently, the spectrum contains a cumulation region $p_{\rm p} \geqslant 400$ MeV/c. However, it shows no peculiarities, such as peaks, confirming the parton character of the process under consideration. That is, it is partons rather than nucleons that are active; they carry a major part of the momentum of a group of several nucleons. The role of nucleon clusters is also manifested in subthreshold reactions of the particle production. For example, the threshold of antiproton production on a nucleon amounts to 6.6 GeV. However, experiment reveals

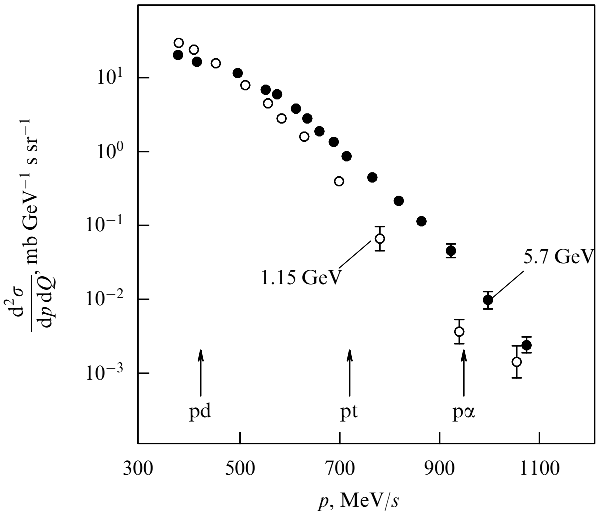

Figure 4. Proton spectrum in the reaction $p + C \to p + X$. Arrows show positions of expected quasielastic maxima.

antiprotons much below the threshold at an energy of 3.9 GeV.

Analysis of a large volume of experimental data disclosed some important features of cumulative processes. The dependence of the cross section on the atomic numbers A_f and A_b of the fragmenting nucleus and beam nucleus, respectively, as well as the cumulative number Q is given by the formula

$$E\,\frac{d\sigma}{dp} = CA_f^n A_b^{1/3} \exp\left(-\frac{Q}{\bar{Q}}\right).$$

The Q-dependence of the cross section is illustrated in Fig. 5.

In the case of pion emission, parameter $n \approx 0.8$ in the pion energy region $T_\pi \leqslant 200$ MeV and tends to a constant value ≈ 1.08 in the $T_\pi \geqslant 300$ MeV region. The change in regime suggests the involvement of the whole nucleus in the cumulative process. Quite a different dependence of the cross section on the atomic number of the nucleus-target is observed for the p, d, and t fragments formation. Index n takes the values of 4/3, 5/3, and 2(!), respectively. The energy spectrum of cumulative particles is fairly well represented by the exponent

$$E\,\frac{d\sigma}{dp} = C\exp\left(-\frac{T}{T_0}\right).$$

Characteristic values of the parameter T_0 are represented in Fig. 6 as functions of the proton beam momentum. Worth noting again is the scaling mode of the process for a beam momentum $p_b \geqslant 4$ GeV/c.

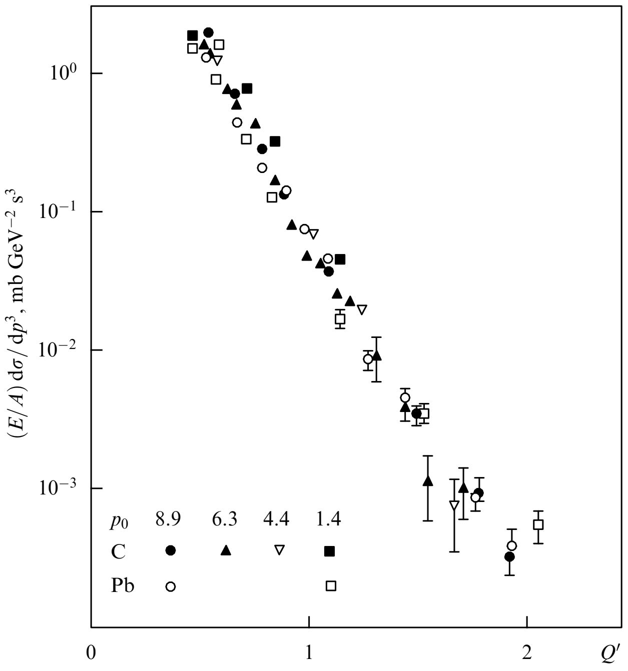

Figure 5. Dependence of pion formation cross sections on the cumulative number Q. C and Pb nuclei undergo fragmentation.

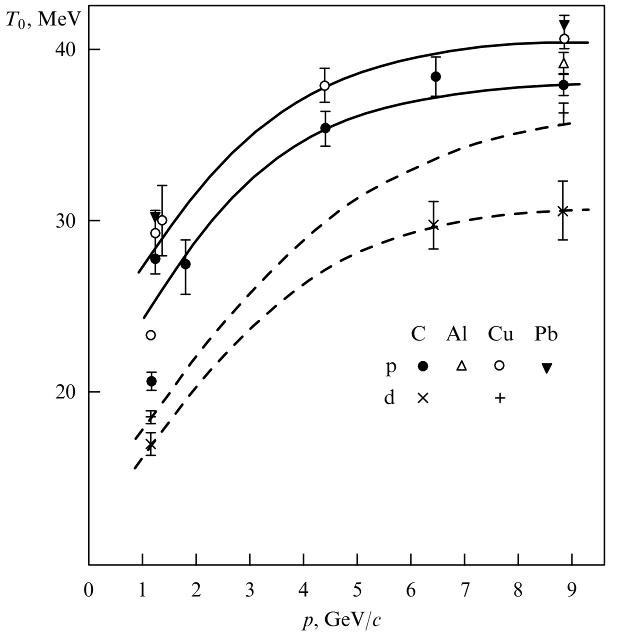

Figure 6. Effective temperature characterizing the emission of cumulative protons and deuterons from different fragmenting nuclei in pA reactions.

6. Investigation of small-angle elastic scattering of particles

An exciting and widely discussed problem in the 1960s was the asymptotics of hadron interactions, namely, the behavior of total cross sections and amplitudes of binary processes as $E \to \infty$. The simplest and therefore most attractive suggestion was based on an optical model in which the total cross sections $\sigma_{\text{tot}} \sim 2\pi r^2$ and the slope of the diffraction cone $b = r^2/2$, $d\sigma/dt \sim \exp(bt)$ tend to a constant value because a hadron as an extended object constitutes an absorbing (grey or black) sphere with constant radius r much bigger than the wavelength ($r \gg \lambda$, $\lambda = h/p$). Accordingly, the real part of the elastic scattering amplitude (determined in optics by the refraction coefficient rather than by diffraction) tends to zero: $\rho(E) = \operatorname{Re} A/\operatorname{Im} A \to 0$. The knowledge of the parameter ρ permits checking dispersion relations linking the real and imaginary parts of the amplitude of particle elastic scattering. They are derived from the principal axioms of the quantum field theory, viz. causality, unitarity, Lorentz invariance, and spectrality. Studies of proton scattering on deuterons provide information about the deuteron form factor and proton – neutron scattering amplitude (especially about its real part). Such data are impossible to obtain by other methods.

The concept of Regge poles was formulated in the early 1960s; it was purported to be the key element of the strong interaction theory. According to reggistics, the major contribution to binary processes and total cross sections at a sufficiently high energy is made by a single pole — the pomeron:

$$\frac{d\sigma(s,t)}{dt} = f(t)\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}, \quad \alpha(t) = \alpha(0) + \alpha' t, \qquad (2)$$
$$\sigma_{\mathrm{tot}}(s) = \sigma_0 + \sigma_1\left(\frac{s}{s_0}\right)^{\alpha(0)-1},$$
$$b(s) = b_0 + 2\alpha' \ln\left(\frac{s}{s_0}\right), \quad \rho \approx 0 .$$

The predictive power of model (2) is poor because it contains an arbitrary function $f(t)$ and two important parameters $\alpha(0)$ and α' determining the type of asymptotics. For $\alpha(0) \leqslant 1$, there is an asymptotics with a decreasing or constant total cross sections; for $\alpha > 1$, the cross sections grow polinomially. To avoid conflict with the Froissart theorem, it is necessary to substantially complicate model (2) by taking into consideration pomeron rescattering (to unitarize the pomeron amplitude). If $\alpha' = 0$, then there is an analog of classical optics with $b = \text{const}$. If $\alpha' > 0$, all diffraction processes include universal logarithmic growth of the b-parameter (and of the interaction region radius).

This posed the problem of experimental verification of relation (2) and determination of at least three important parameters $\alpha(0)$, α', and ρ. Estimates showed that there is a need to perform measurements with high accuracy (within 2 – 3% in differential cross section) and over the entire available energy range $E > 1$ GeV.

Studies of elastic scattering of pions and protons by protons and light nuclei started at JINR at the very first turns of the beam in the SP. The nuclear emulsion initially used gave only general characteristics due to the laborious gathering of statistics. In the early 1960s, the groups led by V A Sviridov and L N Strunov proposed two new highly efficient methods. When observing pion scattering, they used a Wilson chamber filled with gaseous hydrogen. The innovation was a special low-sensitivity chamber operation mode making minimally ionized relativistic particles invisible. This made it possible to pass up to 10^4 particles through the chamber during a single cycle of the accelerator, i.e., three orders of magnitude higher than the usual intensity for such chambers. In this conditions, slow and strongly ionizing recoil protons from elastic scattering were effectively recorded in the gas. The new regime permitted detecting elastic scattering events with an unusually small transferred momentum and gathering large amount of statistics. As a result, parameter ρ was measured for πp and πHe scattering. These data are presented in Figs 7 and 8 [19].

In 1961, an SP internal beam-based facility was created, allowing for the multiple passage of the accelerator beam through a ~ 5 μm thick film target [10]. The experience gained with SP was employed in 1967 to design another installation based on the internal beam of the IHEP U-70 accelerator. It included an essentially new element, namely, a supersonic hydrogen jet target with density ~ 10^{-7} g cm^{-3} [20]. Later on, similar targets were installed in the accelerators of FNAL, CERN, and many other laboratories. A study with a jet target is scheduled at CERN LHC.

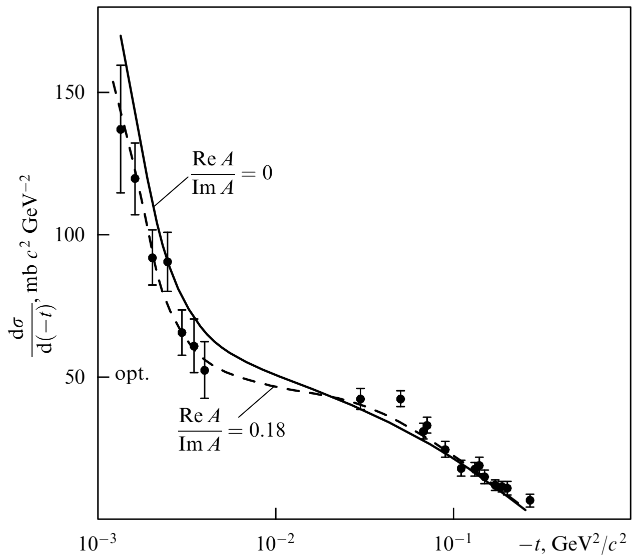

Figure 7. Differential cross section of elastic πp scattering in the Coulomb-nuclear interference area.

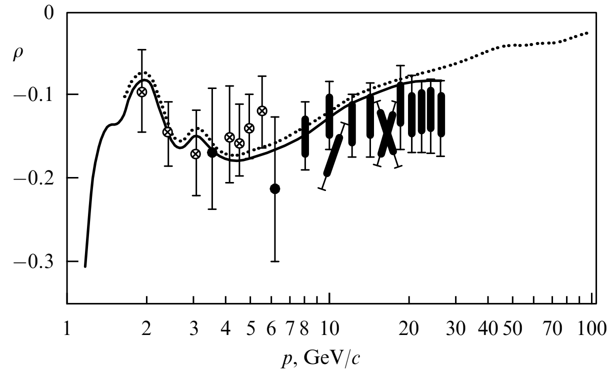

Figure 8. Parameter ρ of elastic πp scattering as a function of π^- beam momentum. Points ⊗ — data obtained at SP. The solid curve is the result of the dispersion relation calculation.

The method using the thin internal target has at least three specific features worth mentioning:

(1) The possibility of precisely measuring the energy and emission angle of a slow recoil particle. We registered protons and deuterons with a minimal energy of 0.4 MeV utilizing semiconductor detectors.

(2) The possibility of scanning over the entire energy range of an accelerator and conducting concomitantly other experiments.

(3) The absence of an ejected beam, which reduces the cost of the facility and allows physics measurements to be started immediately after an accelerator start-up.

The thin internal target technique was applied when studying elastic proton scattering on protons and deuterons [11, 21].

Discussions on the type of asymptotics of hadron processes failed to clarify the problem by mid-1969. Studies of elastic pp scattering in the energy range of 2 – 10 GeV, conducted at JINR, suggested narrowing of the diffraction cone. However, type (2) formulas were inapplicable in such a small-energy range. Results obtained at BNL and CERN in a range from 15 to 24 GeV pointed out the flattening of the functions $\sigma_{\text{tot}}, b(E)$. Nevertheless, the low measurement accuracy and the narrow energy range did not permit a convincing conclusion.

An original methodology and the broad energy range achieved at the then largest U-70 accelerator (1968 – 1972) gave an answer to the question under discussion. In 1968, JINR – IHEP Collaboration initiated a joint study of proton elastic scattering at the very first turns of the beam in the new IHEP 70-GeV accelerator. The initial data about the parameter b obtained at the U-70 were reported at the conference in Lund in the summer of 1969. They unambiguously evidenced the logarithmic growth of the function $b(E)$. The slope parameter of Pomeranchuk's effective pole trajectory proved to be non-zero: $\alpha' = 0.47 \pm 0.09$ [22]. The term 'effective pole' reflects the approximate character of formulas (2). Attempts to formulate a more exact and complete concept of Regge poles are still underway.

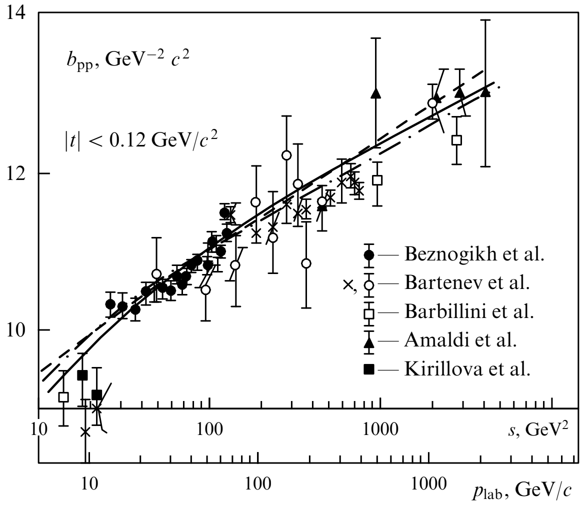

Figure 9. Compiled data on the slope parameter of the pp-scattering diffraction cone. Black circles (Beznogikh et al.) are the data of the JINR – IHEP collaboration.

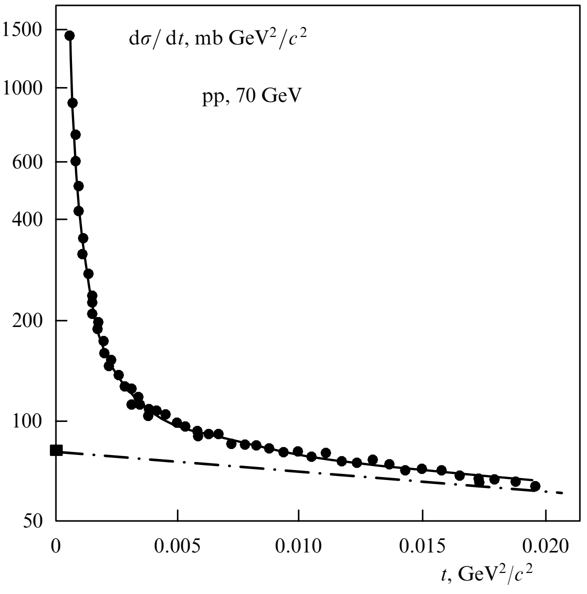

Figure 10. An example of elastic pp-scattering differential cross section in the Coulomb-nuclear interference area.

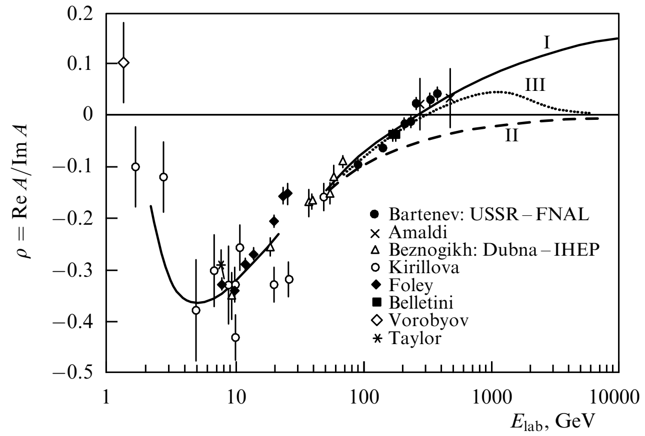

Figure 11. Compiled data on the ρ parameter of elastic pp scattering. Integrated JINR – IHEP data. The curves correspond to different variants of calculations from the dispersion relation.

Figure 9 compiles the most accurate data on the slope parameter $b_{\text{pp}}(E)$ as of 1973. Figure 10 presents an example of a differential cross section of elastic pp scattering. Characteristic measurement accuracy at each point in t is 2%. The Coulomb scattering (and Coulomb-nuclear interference) area and the diffraction cone area $|t| \geqslant 0.01$ GeV$^2/c^2$ are fairly well apparent. The differential cross section in the region of ultimately small values of $|t| \geqslant 0.0007\,\text{GeV}^2/c^2$ (kinetic energy of a recoil proton is $T_{\text{kin}} \approx 0.4$ MeV) was measured to determine the parameter ρ [23]: $d\sigma/dt = |\,i\,\text{Im}\,A + \text{Re}\,A + A_c\,|^2$, $\rho = \text{Re}\,A/\text{Im}\,A$. The knowledge of the function $\rho(E)$ is necessary to verify and further develop a few important aspects of the strong interaction theory, such as dispersion relations, axiomatic field theory, complex moment theory and some others.

Figure 11 summarizes the most accurate data (as of 1973) on the ρ parameter. They are in excellent agreement with calculations from the dispersion relation.

The curves in Fig. 11 were computed from the dispersion relation on the following assumptions about the total cross section behavior:

I. $\sigma_{\text{tot, pp}}$ and $\sigma_{\text{tot,}\,\text{p}\bar{\text{p}}} \sim 0.5 \ln^2(s/122)$;

II. $\sigma_{\text{tot}} = \text{const} = 38$ mb in the region of $E > 120$ GeV;

III. $\sigma_{\text{tot}} = \text{const} = 42.2$ mb in the region of $E > 2{,}000$ GeV.

It is assumed that the Pomeranchuk theorem is fulfilled in all cases, namely

$$\lim_{E \to \infty} (\sigma_{\text{tot, pp}} - \sigma_{\text{tot,}\,\text{p}\bar{\text{p}}}) = 0\,.$$

Model (2) calls for the universal behavior of the function $b_{\text{ab}}(E)$ at a sufficiently high energy. Here, a and b are any pair of hadrons. Experimental data on p, π, K, $\bar{\text{p}}$ scattering on the protons are consistent with this expectation. All processes are controlled by a single parameter α' (the value of which depends on concrete realization of the model and the energy range). There is, however, an exception to rule (2). It is elastic pd and pHe^4 scattering. Experiments were conducted at the accelerators of JINR [24], IHEP [25], and FNAL [26, 27] using the thin internal target technique [20, 21]. The situation is illustrated by Fig. 12 showing energy dependences of the parameters $b_{\text{pp}}(E)$, $b_{\text{pd}}(E)$, and $b_{\text{pHe}}(E)$. Functions $b(E) = b_0 + b_1 \ln E$, $b_1 = 2\alpha'$ for pp, pd, and pHe in the energy range from 2 to 70 GeV have a similar slope: $b_{1,\,\text{pp}} = 0.96 \pm 0.18$,

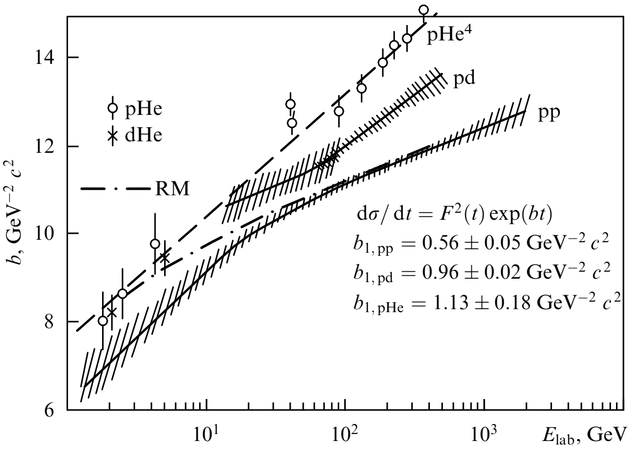

Figure 12. Compiled data on the parameter b of the pp-, pd-, and pHe-scattering diffraction cone. The figure demonstrates the nonuniversal behavior of functions $b_{\mathrm{pA}}(E)$ in the region with $E > 50$ GeV.

$b_{1,\mathrm{pd}} = 1.15 \pm 0.24$, and $b_{1,\mathrm{pHe}} \approx b_{1,\mathrm{pd}}$. But they diverge in the 50–400-GeV region and thereby explicitly break the universality of formulas (2): $b_{1,\mathrm{pp}} = 0.56 \pm 0.05$, $b_{1,\mathrm{pd}} = 0.94 \pm 0.04$, and $b_{1,\mathrm{pHe}} = 1.13 \pm 0.04$. (Values of b are given in GeV$^2 c^2$ units.) Reference [9] considers this problem for the case of pd interaction. It is found that the effective parameter α'_{pA} in scattering on nuclei is modified due to the energy dependence of the mutual nucleon shielding effect (Glauber correction to total and differential cross sections). But the quantitative agreement with experiment was not reached. Reference [29] reports the most complete analysis of elastic pHe scattering taking into account both elastic and inelastic rescattering of a primary particle in the nucleus. But the observable energy dependence $b_{1,\mathrm{pHe}}(E)$ is not obtained. The problem remains to be solved. It may be conjectured that a pomeron appreciably changes its properties as it propagates in nuclear matter (in a modified QCD vacuum).

Studies performed immediately after the commissioning of the U-70 accelerator in the late 1960s were mainframe in the formulation of the pomeron concept and elucidation of the properties of this object. Today, it retains its important role in the description of the dynamics of soft and semihard hadron processes, including inelastic diffraction. The pomeron has acquired the status of an almost real hadron. Experiments on deeply inelastic lepton scattering are aimed at determining its structural function in terms of quarks and gluons.

The problem of hadron elastic scattering is no longer of current importance. However, the anomalous behavior of slope parameters of diffraction cones for proton scattering on light nuclei remains as puzzling as before. Therefore, further precise studies of elastic pA scattering in an energy range above 50 GeV are in order. It is important to make measurements on proton and antiproton beams. This would allow distinguishing the effect of the odderon — an object composed of an odd number of gluons. Theoretically, the odderon is as necessary as the pomeron, but it remains practically unexplored for lack of accurate data on diffraction proton–antiproton interaction. The internal beams of the CERN and FNAL accelerators are suitable for such studies with the use of the methodology previously developed at the SP and U-70 accelerators.

7. Formation of charged particle beams with the help of a bent crystal

The possibility of bending a charged particle beam by directing it through a bent crystal was theoretically predicted by E N Tsyganov in 1976 [30]. Soon after, this surprising effect was observed in the extracted proton beam of the SP [31]. Particle channeling in a crystal had been known before. It was described as localization of the motion of a positively charged particle between crystal planes under the effect of an electrostatic field created by ions near these planes. The angle between the trajectory and the planes being sufficiently small, the particle is reflected from the planes and moves between them. The critical channeling angle is $\theta = \sqrt{2U/pv}$, where U is the depth of the interplane potential well, p is the momentum, and v is the particle's velocity. The trajectory of a negatively charged particle passes near one plane or axis of the crystal. Tsyganov noticed an implicit possibility of realizing channeling in a mechanically bent crystal and bending the beam of particles captured in the course of channeling. In the very first SP experiment, the proton beam with a 8.5 GeV/c momentum was deflected at an angle of 26 mrad by a silicon crystal 5 mm in length. The deflection power of the crystal proved to be equivalent to that of a 60 T magnet! This pioneering study conducted on the SP opened up new avenues of development of experimental techniques, such as beam extraction from the accelerator, formation of secondary particle beams, creation of essentially new focusing elements, and measurements of beam emittance and magnetic moments of short-lived particles [32]. It was the first extraction of the beam from the SP, schematically represented in Fig. 13. This method was later tested at the CERN SPS and at the FNAL Tevatron. A few extracted 70 GeV proton beams were produced using bent crystals at the IHEP U-70 accelerator.

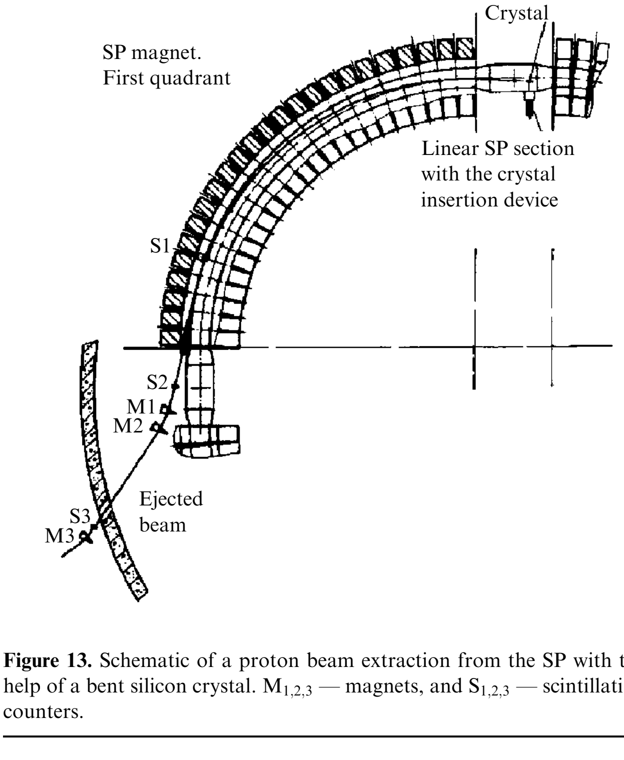

Figure 13. Schematic of a proton beam extraction from the SP with the help of a bent silicon crystal. $M_{1,2,3}$ — magnets, and $S_{1,2,3}$ — scintillation counters.

8. Conclusion

To conclude, the most important SP-based methodical and physical studies were highly appraised and awarded State Prizes. The laureates and their works are as follows:

1959 — V I Veksler (JINR), F A Vodop'yanov, D V Efremov, L P Zinov'ev (JINR), A A Kolomenskii, E G Komar, A L Mints, N A Monoszon, V A Petukhov (JINR), M S Rabinovich, S M Rubchinskii, and A M Stolov — design and construction of 10-GeV synchrophasotron.

1983 — Yu K Akimov, V A Nikitin, B A Morozov, Yu K Pilipenko, L S Zolin, S V Mukhin, M G Shafranova, V A Kopylov-Sviridov, A A Kuznetsov (JINR), A A Vorob'ev (LINP), E L Feinberg (FIAN), and V A Tsarev (FIAN) — diffraction scattering of protons at high energies.

1985 — G P Zhukov, I F Kolpakov, A N Sinaev et al. — development and mass production of the CAMAC international standard-based automation system for scientific and technical studies.

1986 — Yu V Zanevskii et al. — development and application of nuclear physical methods and instruments for molecular biology studies.

1986 — N N Govorun, V P Shirikov et al. — development and application of computer software for engineering calculations and designing complex technical systems.

1988 — A M Baldin, P N Bogolyubov, V A Matveev, R M Muradyan, and A N Tavkhelidze — discovery of a new quantum number (color) and elucidation of dynamic patterns in the quark structure of elementary particles.

1992 — V S Alfeev, Z V Borisovskaya et al. — design and creation of cost-effective superconducting magnets for high-energy accelerators.

1996 — M D Bavizhev, V I Kotov (IHEP), A I Smirnov (PINP), A M Taratin, E N Tsyganov (JINR) et al. — development of new methods for handling particle beams with the help of bent crystals.

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From synchrophasotron to Nuclotron

A D Kovalenko

1. Introduction. The phase stability principle — the Gordian knot cut!

I have the honor of representing accelerator physicists, engineers, and technicians, in fact the entire staff of the Laboratory of High Energies (JINR) founded by V I Veksler, an outstanding scientist who made a major contribution to world science and international collaboration of scientists, at this solemn session celebrating the 100th anniversary of his birth. People of my generation, those born half a century after Vladimir Iosifovich and involved, as fate willed, in the construction of accelerators and the production and applica-