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Pion, Pion–Pion, and Pion–Nucleus Interactions

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Abstract—This survey is devoted to describing the early studies of I. I. Gurevich on pion physics that were performed by the photoemulsion method and the studies of the pion–pion interaction that were made by his colleagues on the basis of the hydrogen–bubble-chamber and the magnetic–spectrometer method (as well as on the basis of the photoemulsion method). Two approaches—an extrapolation of experimental data from the physical region to the pion pole and a theoretical calculation based on the Roy integral equations—are used to deduce information about the pion–pion interaction. The first results obtained for pion–pion and pion–nucleus interactions in the experiments that are being currently performed in Brookhaven and at CERN (ππ interaction) and at TRIUMF (Canada) and in Brookhaven (pion–nucleus interaction) are presented, along with the existing theoretical concepts in these realms of physics.

One of the authors of the present article (K. N. Mukhin) had had a privilege to associate with I. I. Gurevich (further I. I.) for about 45 years, not only at the laboratory and at the seminars that he headed but also during our mutual pedagogical activities at the Moscow Engineering Physics Institute (we delivered lectures in neighboring rooms and went home together, visiting bookshops on the way), at his home (editorship work), and even during vacations. Of course, physics was one of the permanent topics of our association. I. I. loved any kind of physics, including so-called general physics, nuclear physics, elementary-particle physics, and astrophysics. But he was especially fond of nuclear physics, nourishing tenderness, in particular, to the simplest version of the nuclear reactor—namely, the uranium–graphite reactor employing natural uranium. He used to say, “Only imagine what a wonderful combination made it a physical reality. If the cross section for 235U fission induced by thermal neutrons and the number of secondary neutrons formed had been slightly smaller and if the cross section for resonance-neutron capture by 238U had been slightly larger, the success could not have been achieved.”

It is no wonder that the neutron was of course his first love in elementary-particle physics. But when the problem was by and large solved (owing, in particular, to a very serious contribution of I. I.), there appeared his second love—the pion (after that, the muon; then, the monopole; and, finally, the neutrino). In the present article, we would like to tell how this second love of I. I. began, how he could inspire this feeling in the souls of some of his collaborators, and how investigation with I. I. into the physics of pions and of pion–nucleus interaction made its first steps; we will also list the results at which these lines of investigation arrived today.

Apart from describing our studies, we will discuss, in the last sections of this article, the currently prevailing situation in the theoretical and experimental physics of the pion–pion interaction—in particular, the first results of unique experiments that are being presently performed in Brookhaven and at CERN. We will also give an account of intriguing data from the latest experiments that studied pion-production processes in pion–nucleus interactions.

1. STUDIES OF I. I. GUREVICH AND HIS COLLEAGUES ON PION PHYSICS

As is well known, pions, which were predicted by Yukawa as quanta mediating strong interaction, were discovered in the composition of cosmic rays in 1947 by the photoemulsion method. Both these circumstances (the very fact of this discovery and the method by which it was made) strongly affected the attitude of I. I. to the pion as one of his favorite particles. As soon as the synchrocyclotron of the Joint Institute for Nuclear Research was commissioned at Dubna, I. I. headed a group of his collaborators who began conducting experiments devoted to pion physics by using precisely the photoemulsion method.

I. I. had been acquainted with the photoemulsion method for studying the properties of elementary particles since 1935, when, together with A. P. Zhidanov, he tried to improve this method, which was first developed by L. Mysovskii and P. Chizhov in 1927 [1]. At the time that we are now describing (the late
1940s and the early 1950s, I.I. continued intensively developing this procedure, organizing, in his division, a photoemulsion group headed by D.M. Samoilovich, who evolved and fabricated special thick-layered nuclear photographic plates that were capable to detect the tracks of singly charged elementary particles. In the same years, another collaborator of I.I. (V.V. Alpers) developed the emulsion-chamber procedure (it employs stacks of emulsion layers without glass, where, owing to the common coordinate grid, it is possible to trace the tracks of particles that go over from one layer to another) [2], which is more elaborate than that based on photographic plates. It is precisely these plates and chambers that were used in the pion-physics studies that were performed by I.I. and his colleagues and which are described below. (For purely technical reasons, these studies were published much later than they had been performed or have not been published altogether.)

One of the first studies of I.I. and his colleagues was devoted to determining the pion mass by the photoemulsion method that involves counting the developed grains on the tracks of pions (π) and protons (p). Negative pions were produced in the interaction of 560-MeV alpha particles with lead nuclei in a special device installed in the synchrocyclotron chamber and, after being deflected by the magnetic field of the accelerator, were incident on photographic plates at sliding angles. The geometry of the experiment was chosen in such a way that slow negative pions of energy in the range 1–30 MeV hit the photographic plates.

Horizontal tracks situated rather far off the emulsion surface and the glass were selected for viewing and measurements. Grains were counted at a 2025 magnification by using a dedicated procedure for analyzing the ends of the tracks, where the density of the grains was so high that they formed so-called conglomerations. The counting yielded the dependences \( N(R) \), where \( N \) is the number of the grains and \( R \) is the residual range (that is, the particle range measured from the point of its stopping). From the theory of the method, it follows that \( N = R_\varphi(R/m) \); that is, the pion mass can be estimated by comparing \( N_\pi(R_\varphi) \) and \( N_p(R_\varphi) \) at specific values of \( R_\pi \) and \( R_p \) (protons, whose mass is known, served as a reference).

For the negative-pion mass, the processing of these data yielded the value

\[
m_\pi^- = (273.6 \pm 2.9) m_e,
\]

which was the closest to the modern value (\( \sim 273.1 m_e \)) among all of the values obtained at that time in other laboratories worldwide. Unfortunately, we were unable to publish this study, and the traces of it remain only in the form of a report in the archives of our institute [3].

Within the same period (1950–1952), I.I. and his collaborators performed investigations in which they exposed nuclear photographic plates and emulsion chambers to cosmic rays. The irradiation of photographic materials was implemented in balloon-borne experiments (the balloons used were launched in Dolgoprudny) performed by physicists from the Research Institute of Physics (Moscow State University), who were directly involved in cosmic-ray studies. Our efforts were aimed at discovering, in cosmic rays, particles of mass that would have intermediate values between the pion and the proton (this was a popular topic of investigation at that time), but our attempts proved to be futile [4, 5].

In 1952 and 1553, I.I. relaunched their investigations at the synchrocyclotron, where they explored the features of the production of slow charged pions on photoemulsion nuclei exposed to 460-MeV protons and to neutrons of 400-MeV effective energy [6]. Two photoemulsion chambers, each consisting of 20 photoemulsion layers and having a total thickness of 6 mm, were used in that study. One of the chambers was exposed to an extracted beam of protons, while the other was exposed to a neutron beam.

The use of the emulsion-chamber procedure enabled us to trace the entire path of charged pions from the point of their ionization stopping to the production vertex. This made it possible to observe a large number of stars\(^1\) associated with the production of charged pions and to construct angular and energy distributions of product pions in the region of low energies.

Inspecting the resulting curves, one can clearly see that the energy spectra of negative and positive pions are shifted with respect to each other by \( \Delta \approx 15 \) MeV. This shift is naturally explained by the effect of the Coulomb barrier, whose mean height for photoemulsion nuclei with respect to singly charged particles is 7.5 MeV. In addition, the cross sections for the production of slow (\( 0 < E < 40 \) MeV) charged pions were estimated at

\[
\sigma_{\pi^+} = (2.9 \pm 0.9) \times 10^{-27} \text{ cm}^2, \quad (2)
\]

\[
\sigma_{\pi^-} = (1.3 \pm 0.5) \times 10^{-27} \text{ cm}^2,
\]

\[
\sigma_{\pi^+ + \pi^-} = (4.2 \pm 1.4) \times 10^{-27} \text{ cm}^2,
\]

and the ratio of the numbers of product positive and negative pions was found to be

\[
\pi^+ / \pi^- = 2.5 \pm 0.5. \quad (3)
\]

\(^1\)By a star, we mean a microphotograph of a particle-nucleus interaction resulting in the formation of starlike rays of tracks generated by charged particles emitted from the nucleus involved.