FISSION OF URANIUM NUCLEI AND PRODUCTION OF MULTI-CHARGED FRAGMENTS ON EMULSION NUCLEI BY HIGH-ENERGY POSITIVE π MESONS

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The interaction between 280-Mev π^+ mesons and uranium nuclei, accompanied by fission, was studied by means of nuclear emulsions. It has been concluded, from an analysis of the light charged particles emitted in fission, that the absorption of π^+ mesons occurs predominantly in interactions involving a pair of nucleons (n, p). The main features of uranium fission induced by high-energy π^+ mesons are investigated. Some peculiarities of production of multi-charged ($Z \geq 4$) fragments on emulsion nuclei by high-energy positive π mesons are noted. An estimate is given for the cross section for production of such fragments on heavy emulsion nuclei (Ag, Br).

THE present work is devoted to two problems connected with the interaction between high-energy π^+ mesons and complex nuclei: the fission of uranium nuclei induced by 280-Mev π^+ mesons, and the production of multi-charged fragments on emulsion nuclei by π^+ mesons of the same energy.

The work has therefore been divided into two parts, corresponding to the above phenomena.

1. INTERACTION BETWEEN 280 Mev π^+ MESONS AND URANIUM NUCLEI ACCOMPANIED BY NUCLEAR FISSION

In the study of the properties of π mesons, which are so important for the problem of nuclear forces, attention has been mainly given to the elementary interactions of mesons with protons and deuterons. Many investigations have been carried out, and interesting qualitative and quantitative results have been obtained. A number of processes going on in the nucleus can be observed in interactions between π mesons and complex nuclei, which makes it difficult to interpret the primary interaction between mesons and the nucleons of the nucleus. Some problems, however, such as the question of whether the meson is absorbed in interaction with a pair of nucleons or with several nucleons, or whether the interaction between a π meson and the nucleons can be considered as consecutive interactions with separate nucleons, etc., can be solved only by studying the interaction with complex nuclei.

Majority of the investigations devoted to these problems have been carried out by means of nuclear emulsions and have been mainly concerned with the interaction between comparatively low-energy positive and negative π mesons ($E < 150$ Mev) and emulsion nuclei. The interaction between high-energy π mesons ($E > 150$ Mev) and nuclei of the emulsion has been studied mainly for the case of negative π mesons.[1-6] Interactions between fast mesons with Pb, C, Be, Al, and Cu nuclei have been studied mainly by means of cloud chambers[7-10] and scintillation counters.[11-13]

According to our present ideas, a high-energy meson colliding with a nucleus can, in interaction with nucleons, undergo elastic or inelastic scattering, scattering accompanied by a change of charge, or absorption. Energetic nucleons due to scattering or meson absorption, can collide with other nucleons (cascade process) in traversing the nucleus and leave the nucleus altogether (if their energy is sufficient). The excited nucleus loses energy emitting nucleons.

A certain difficulty is encountered in interpreting interactions with the emulsion nuclei due to the presence of both light and heavy nuclei in the emulsion. Besides, the result of the primary interaction between a π meson and an emulsion nucleus is strongly masked by the large number of charged particles "evaporated" from the nucleus.

There are some advantages in studying the interaction between high-energy positive π mesons with uranium nuclei. Firstly, such events can be easily identified by subsequent fission of the uranium nucleus which is bound to happen in the majority of cases. Fission serves, therefore, as an identification mark for uranium nuclei. Secondly,

TABLE I

Particle type and energy	Relativistic emulsion		Emulsion P-9	
	Mean number of charged particles per fission	Forwards/ backwards ratio	Mean number of charged particles per fission	Forwards/ backwards ratio
π^+, $E = 280$	2.1 ± 0.17	1.1 ± 0.2	1.01 ± 0.05	1.27 ± 0.17
p, $E = 350$	0.9—1.0	~3.4	0.60 ± 0.06	1.7 ± 0.2
p, $E = 140$	0.40 ± 0.06	4	0.25 ± 0.02	2.6 ± 0.5
Slow π^- mesons	~0.12		0.10 ± 0.02	

only a small number of charged particles is expected to evaporate from a uranium nucleus since, in heavy nuclei, excitation energy is dissipated mainly through the emission of neutrons. In consequence, it is easier to identify charged particles emitted as the result of interaction between a π meson and nucleons.

We have selected and studied the interaction events accompanied by fission. An analysis of the charged particles emitted in such events makes it possible to draw certain conclusions concerning the absorption of π^+ mesons. Besides, we studied the fission of U nuclei induced by high-energy positive mesons, in view of the lack of data on that subject.*

Uranium was introduced into the emulsions by soaking the plates in a 4% aqueous solution of $UO_2Na(C_2H_3O_2)_3$. In that way it was possible to introduce $\sim 10^{20}$ uranium nuclei into 1 cm^3 of emulsion. The plates were then irradiated. Positive 300-Mev mesons were produced by the synchrocyclotron of the Joint Institute for Nuclear Research. The plates were bombarded with 280-Mev mesons selected from the beam by means of a copper absorber.

Two types of special fine-grain emulsions† were used in the experiment. The first type was capable of recording relativistic particles of minimum ionization, while the second (type P-9) had a sensitivity threshold for 45 to 50-Mev protons. Both these emulsions have high sensitivity and good discrimination for particles of different charge. The relativistic emulsion made it possible to detect all charged particles accompanying the interaction and, consequently, to obtain a full picture of the event (as far as charged particles were concerned). This emulsion cannot, however, be irradiated by a large meson flux (because of the resulting background which makes scanning difficult), and the number of fission events observed in this emulsion is small. A large number of fission events has been observed and studied in the P-9 emulsion, which could be irradiated with a large meson flux. The data thus obtained augmented substantially those obtained by means of the relativistic emulsion, and made it possible to study the main features of uranium fission induced by high-energy positive mesons.

We found and studied 73 cases of fission of the U nucleus, induced by fast π^+ mesons in the relativistic emulsion, and 460 cases in the P-9 emulsion. The majority of fission events induced by high-energy π^+ mesons is accompanied by emission of charged particles.

The mean number of charged particles per fission induced by π^+ mesons ($E = 280$ Mev) for the two types of emulsion (columns 2 and 4), and the angle formed by these particles with the direction of the incident π^+ meson (columns 3 and 5), are given in Table I. Analogous data on fission induced by 350-Mev and 140-Mev protons and slow negative mesons, obtained by us earlier, are included for comparison.

It follows from the second column of the table that, in relativistic emulsion, the mean number of charged particles per fission induced by fast π^+ mesons is much larger than the mean number of charged particles emitted in fission induced by 350-Mev and 140-Mev protons. It follows from the comparison of the mean numbers of charged particles in fission induced by π^+ mesons, observed in different emulsions (columns 2 and 4), that most of these particles have a high energies, $E > 50$ Mev.

Let us consider now the angles of emission with respect to the fission producing particle, given in the third column of the table for relativistic emulsion (the ratio of the number of particles emitted in the forward direction to the number of particles emitted backwards). For the case of π^+-meson induced fission, the distribution is nearly isotropic (1.1 ± 0.2), while for fission induced by fast protons there is a strong preponderance of forward-moving particles (the forward to backward ratio

*The only data available are on uranium fission induced by slow negative mesons[14-17] and on the fission of Hg induced by 150-Mev π^- mesons.[18]

†The emulsions were prepared in the laboratory of Prof. N. A. Perfilov.

is > 3).

The above data on the mean number of charged particles and their direction do not contradict the assumption that the majority of charged particles, associated with fission induced by fast mesons, results from the primary interaction between the π^+ meson and nucleons of the nucleus. These particles may comprise both scattered protons and particles ejected by them in a cascade process, and protons produced in the absorption of the meson together with charged particles ejected by them from the nucleus in a cascade process. The number of charged particles evaporated by the uranium nucleus is small.

If the interaction in π^+ meson absorption involves a (n, p) pair, we should observe two protons emitted at 180° to each other in c.m. system. High-energy cascade particles ejected by these nucleons preserve, essentially, the directions of the primaries. If the absorbed π^+ meson interacts with several nucleons, there is no preference for large angles (> 120°) between emitted particles. We have carried out an analysis of the light charged particles, accompanying the π^+-meson induced fission in relativistic emulsion. The angles (in space) between emitted protons, and their energies, were measured in events accompanied by the emission of two or three protons. The energies of these protons were measured by the grain density method. The dependence of the spatial angle of proton pairs on the sum of the energies of these protons is shown in Fig. 1. It can be seen that the

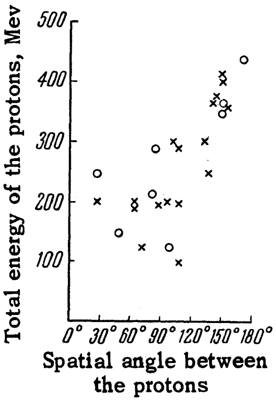


FIG. 1. Dependence of the spatial angle between protons of a pair on the total energy of the protons: o – for events with emission of two protons, × – for events with emission of three protons (relativistic emulsion).

angle increases with the energy of emitted protons, approaching 150° for a pair energy equal to ~ 400 Mev. This is in agreement with the assumption that the 280-Mev π^+ mesons are, mostly absorbed in interaction with the (n, p) pairs.

A large number of the charged particles accompanying the fission of uranium induced by π^+ mesons is, evidently, produced in a cascade process. It is possible, however, for example in emission of two protons after the absorption of a π^+ meson, that one of the protons leaves the nucleus without undergoing a collision with other nucleons in the nucleus, while the other collides first with a neutron. In the emission of three protons, it is possible that one of the two protons produced as the result of π^+ absorption leaves the nucleus without collision, while the other ejects another proton. A microphotograph of such an event is shown in Fig. 2.

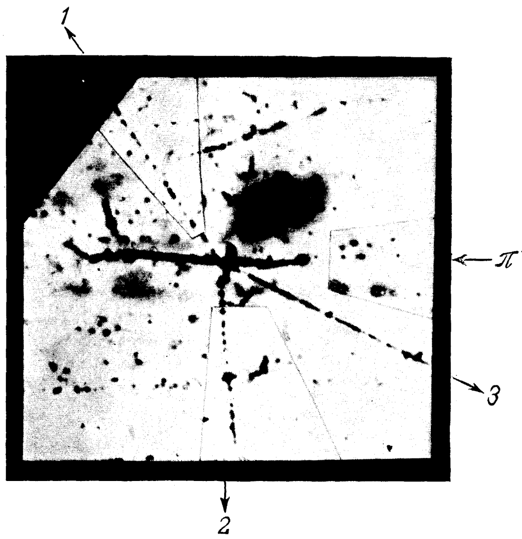


FIG. 2. Fission of a uranium nucleus induced by a 280-Mev π^+ meson. 1 – proton of ~ 220 Mev, 2 – proton of ~ 100 Mev, 3 – proton of ~ 80 Mev (Magnification 1550 ×).

The assumption that the mesons are mostly absorbed by (n, p) pairs is indirectly confirmed by data obtained by means of the P-9 emulsion. In this emulsion we measured the projection of the angles between emitted protons. The solid line in Fig. 3 illustrates the dependence of the number of proton pairs on the angle (projected)

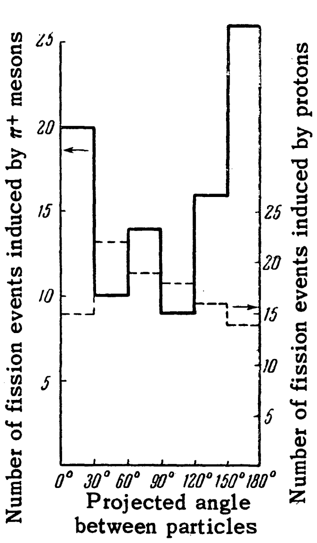


FIG. 3. Dependence of the number of emitted pairs on the projected angle between the particles of the pair: solid line – for π^+-meson induced fission, dotted line – for high-energy proton induced fission (emulsion P-9).

between the components of a pair. We note a marked increase in the number of events with large angles (> 120°). In Fig. 3 we included for comparison (dotted line) a similar dependence for protons emitted in uranium fission induced by high-energy (460 to 660 Mev) protons, investigated by us earlier in the P-9 emulsion. The histogram is constructed also for fission events accompanied by the emission of two and three particles. The charged particles recorded in the emulsion P-9 in proton-induced fission events are mainly evaporated protons. These should possess an almost isotropic distribution of the angles of emission, very different from the curve obtained for fission induced by fast π^+ mesons. This effect can be seen in Fig. 3. Consequently, the preponderance of large angles between emitted protons (in fissions induced by π^+ mesons) can be explained by the presence of cascade particles, ejected from the nucleon by the proton pair originating in the absorption of π^+ meson.

The above analysis of fission events induced by π^+ mesons in both types of emulsion, relativistic and P-9, makes it possible to conclude that, for the most part, the π^+ mesons are absorbed in interaction with the (n, p) nucleon pairs.[34] The data obtained in the present experiment do not exclude the possibility that the π^+ mesons may be absorbed in the first interaction, without previous energy loss.

All fission events detected in the relativistic emulsion were specially examined for the presence of a scattered meson emitted from the nucleus undergoing fission. In seven cases out of 73, a π^+ meson with energy greater than 45 to 50 Mev was observed in addition to light charged particles.*

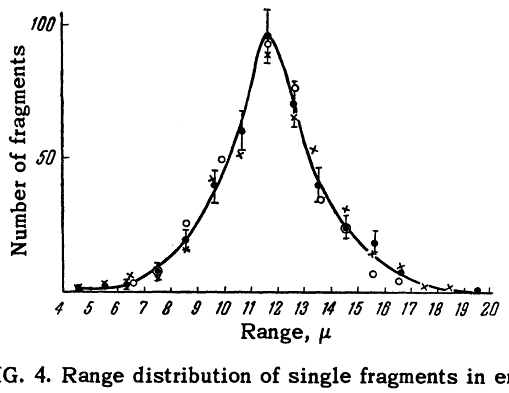


FIG. 4. Range distribution of single fragments in emulsion for fission events, induced by: ● – 280-Mev π^+ mesons ○ – 350-Mev protons, × – slow π^- mesons.

*It should be noted that only mesons with energies greater than > 45 to 50 Mev can be properly identified from the ratio of the grain density of the given particle to the grain density of a particle with minimum ionization.

This amounts to ~10% of the interaction events leading to fission.

The fission of uranium nuclei induced by positive mesons can therefore be explained as due to passage of fast nucleons through the nucleus, originating in meson absorption, and to meson scattering with large energy transfer.

We shall note the following features of uranium fission, induced by 280-Mev π^+ mesons, which were obtained in our experiment: The solid curve in Fig. 4 represents the range distribution of single fragments of uranium fission induced by 280-Mev π^+ mesons. The curve has a maximum indicating a predominantly symmetric fission. The dots in the figure represent distributions in fission induced by 350-Mev protons[19] and by slow π^- mesons.[14] It can be seen that, within the limits of errors, all the points lie on the curve. The mean total range of fragments in π^+-meson induced fission events, equal to 23.5 μ, coincides, within experimental error, with that in fission induced by 350-Mev and 140-Mev protons (23.1 μ and 23.3 μ respectively) and by slow π^- mesons (23.7 μ).

We estimated the cross-section for the fission of uranium by 280-Mev π^+ mesons. The cross-section was determined both from the experiments with the relativistic emulsion and those with the P-9 emulsion. The number of uranium nuclei in the emulsion was measured by counting the number of α-particles emitted by uranium. The meson flux in the relativistic emulsion was measured by counting the meson tracks, and was calculated for the P-9 emulsion from the irradiation time. According to our measurements, the cross-section for the fission of uranium, induced by 280-Mev π^+ mesons, is equal to $(1.0 \pm 0.2) \times 10^{-24}\,cm^2$.

2. PRODUCTION OF MULTI-CHARGED ($Z \geq 4$) FRAGMENTS ON EMULSION NUCLEI IN INTERACTION WITH 280-Mev POSITIVE MESONS

The mechanism of production of multi-charged fragments accompanying the interaction between fast mesons and nuclei has not been fully explained. The production of multi-charged fragments can be observed not only in interactions of cosmic rays,[20-25] but in interactions between nuclei and nucleons with energy of the order of several hundred Mev.[26-32] An extensive study,[33] devoted to the production of multi-charged fragments on emulsion nuclei by high energy protons, has shown that the process cannot be explained by an evaporation or a cascade theory, but requires special assumptions on the interaction between fast protons and nuclei. In connection with the above, it is of interest to investi-

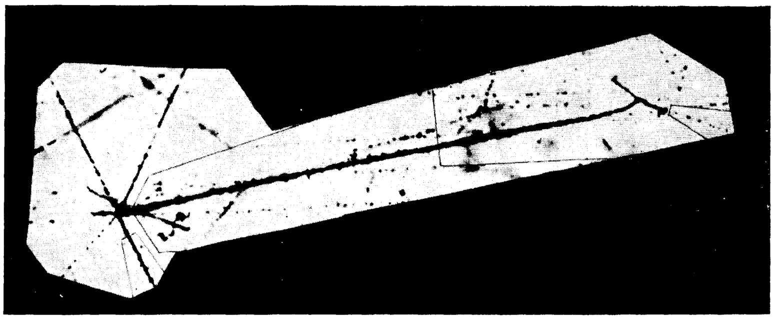


FIG. 5. Interaction between a π^+ meson (E = 280 Mev) and a heavy emulsion nucleus, accompanied by the emission of a multi-charged fragment (B^5_8) (Magnification 1000 ×).

TABLE II

	Relativistic emulsion		Emulsion P-9		Forwards/backwards ratio of fragments (both emulsions)
	Mean number of prongs per star	Forwards/backwards ratio of prongs	Mean number of prongs per star	Forwards/backwards ratio of prongs	
Stars with multi-charged fragments produced by 280-Mev π^+ mesons	5.4±0.2	1.3±0.3	4.9±0.2	1.1±0.1	3.2±1
Stars without multi-charged fragments, produced by 280-Mev π^+ mesons	<4.9±0.1 (∼3.9)	1.2±0.1	<4.4±0.1 (∼3.3)	1.15±0.08	

gate the production of such fragments by high-energy π mesons as well.*

In the experiments with the relativistic emulsion we recorded 24 interaction events between 280-Mev π^+ mesons and emulsion nuclei, accompanied by production of multi-charged ($Z \geq 4$) fragments. Sixty-five similar events were observed in the P-9 emulsion.

A microphotograph of an interaction between a π^+ meson and a heavy emulsion nucleus, accompanied by emission of B^5_8, is shown in Fig. 5 (relativistic emulsion).

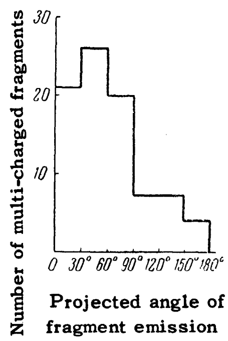
Some data on stars, accompanied by emission of multi-charged fragments and unaccompanied by such an event, are given in Table II.

The mean number of prongs in stars, with and without emission of multi-charged particles is given in the first and third column of the table for the two types of emulsion. The mean number of prongs in stars unaccompanied by fragment emission should be lower than that given in the table, since such stars with zero and one charged particles are not noted in scanning, while stars with two charged particles are also partially overlooked. Approximate values of the mean number of prongs, calculated with allowance for missed stars, are given in parentheses.

The ratios of the numbers of light charged particles emitted forwards (with respect to the incident π^+ meson) to the number of charged particles emitted backwards are given in the second and fourth columns. The same ratio for the fragments, measured by means of both emulsions, is given in the last column.

The above data indicate a certain similarity between the production of multi-charged fragments in interaction between high-energy π^+ mesons and emulsion nuclei and the production of these fragments in interaction involving the emulsion nuclei and high-energy protons.[33] It follows from Table II that, for π^+ mesons, production of fragments is more probable in events with many prongs. The same has been noted for fast protons.[33]

FIG. 6. Distribution of multi-charged fragments as function of the projected angle of emission relative to the π^+-meson direction.



The angular distribution of the emitted multi-charged fragments about the direction of the incident π^+ meson is of special interest. It has been found that the emitted fragments are directed predominantly forwards. This follows from the last column of Table II (forwards/backwards = 3.2) and from Fig. 6, representing the dependence of

*The presence of such fragments in interaction between 750-Mev π^- mesons and emulsion nuclei (16 cases) is mentioned in reference 2.

the number of emitted fragments on the projected angle of emission relative to the direction of the incident meson. It should be noted that a similar preponderance of multi-charged fragments emitted forwards has been observed for production of these fragments on emulsion nuclei by high-energy protons.[33] All other light charged particles produced in nuclear disintegrations induced by π^+ mesons are emitted almost isotropically (columns 2 and 4).

The cross section for the production of multi-charged fragments on heavy emulsion nuclei (Ag, Br) by 280-Mev π^+ mesons, estimated from the data obtained in the present work, equals $(0.62 \pm 0.2) \times 10^{-27}\,\text{cm}^2$.

We investigated the possibility of multi-charged fragment production in events in which the incident π^+ meson is not absorbed in the nucleus, but only scattered. We studied the light charged particles emitted in addition to the fragments in stars, observed in the relativistic emulsion. The ratio of grain density of the tracks of fast particles to the grain density of tracks of particles with minimum ionization was measured. As particles with minimum ionization we chose the primary-meson background recorded in the relativistic emulsion. This made it possible to detect scattered mesons of > 45 to 50 Mev.

An emitted π meson, accompanying a multi-charged fragment, was found in five events out of the 24 stars detected in the sensitive emulsion. Four events were identified by a low value of I_{part}/I_{min}, and the fifth from the general energy balance of all emitted charged particles. It follows that the absorption of the meson is not necessary for the production of a multi-charged fragment by a fast meson.

The preliminary data given above do not contradict the assumption that the production of multi-charged fragments in the interaction between fast π^+ mesons and nuclei can be induced by fast nucleons produced in the first scattering act of the π^+ meson on a nucleon accompanied by a large energy transfer. This fact could explain to a certain extent the angular distribution of emitted fragments. It can also be maintained, however, that the angular distribution observed is not contradicted by the assumption that the fragments are produced in the nucleus in the first inelastic interaction of the meson.

In conclusion, the author wishes to express his gratitude to B. S. Neganov of the Joint Institute of Nuclear Research for his help in irradiating the plates with π^+ mesons, and to Prof. N. A. Perfilov for his constant interest in the work.

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SURFACE IMPEDANCE OF SUPERCONDUCTING CADMIUM

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The apparatus described here can be used to measure the surface impedance of a metal at a wavelength of 3.2 cm in the "super-low" temperature region of $\sim 0.1°K$. The complex surface impedance of a cadmium single crystal has been measured in the temperature interval between 0.1 and 0.6°K. The results of the measurements are analyzed. The penetration depth of the electromagnetic field in the superconducting cadmium has been determined and found to be $\delta_0 = (13 \pm 1.4) \times 10^{-6}$ cm for $T \rightarrow 0$.

THE measurement of the surface impedance of superconductors is particularly interesting in the frequency range satisfying the condition $h\nu/kT_c \gtrsim 1$, which can also be written as $\lambda T_c \lesssim 1$ (λ = wavelength in cm, T_c critical temperature of the superconductor in °K). This condition can be satisfied by two different methods: by decreasing the wavelength λ of the applied electromagnetic radiation, and by investigating superconductors with lower critical temperatures T_c.

Until now most investigators have followed the first method[1-4] up to the present limits of radio techniques ($\lambda \sim 0.2$ cm). Only preliminary work has been carried out with the second method.[5,6] In this case, as in all work in this field, the temperature of the sample (Al) was reduced to 0.85°K by pumping off the liquid helium which cooled the whole of the apparatus under investigation.

This paper describes apparatus for the measurement of samples cooled to $\sim 0.1°K$ by the magnetic method (with ammonium iron alum used as the cooling agent). This makes possible a value $h\nu/kT_c = 0.9$ in investigations of cadmium at a wavelength of 3.2 cm, for example. This value is reached only at $\lambda = 0.46$ cm when working with tin. One of the features of the apparatus is that

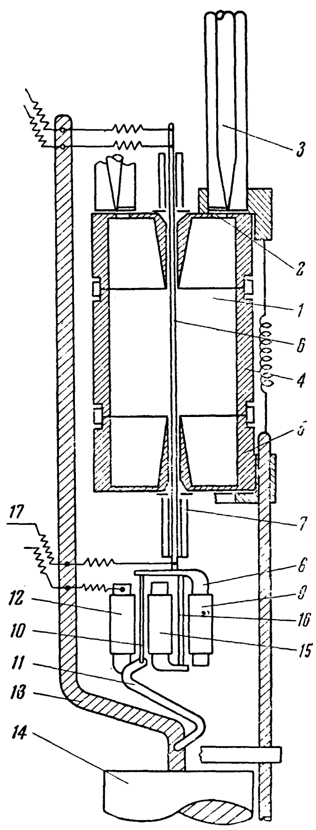

FIG. 1. Outline of the apparatus. On the right are shown some constructional details of the apparatus. The vacuum jacket is not shown.