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Oscillographic Determination of Energy of Electric Explosion of Wires

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A procedure is described for oscillographic determination of the energy of the electric explosion of wires; this procedure is free of the errors due to the inductive distortion of the explosion oscillograms. It is shown that in high-voltage electric explosions the wire resistance is not a single-valued function of the amount of energy supplied.

1. INTRODUCTION

ARTICLES devoted to various aspects of the investigation of electric explosion of wires have been appearing recently with increasing frequency[1-10]. The interest in this phenomenon is due principally to the fact that it permits investigation of the properties of a substance to which a large quantity of energy is supplied (behavior of substances at high temperatures, transitions between different aggregate states, emission properties, electric resistance, etc.). It is evident that as accurate a determination as possible of the energy supplied is essential in these investigations. The energy is usually calculated from the current and voltage oscillograms. In view of the short duration of the explosion process, energy losses due to thermal radiation, thermal conduction, convection, etc., are neglected.

Given below are experimental results on the oscillographyof electric explosion of wires, performed over a relatively wide range of voltages across the capacitor of the explosion circuit. A "current-measuring resistor," described in Ref. 6, was used to obtain current oscillograms free of any inductive distortion whatever. The energy supplied to the wire is calculated only from current oscillograms and from known values of the initial capacitor voltage and capacitance, and from the inductance of the explosion circuit. The data obtained point to several conclusions concerning the variation of the wire resistance with the energy supplied and with the relative energy balance during the electric explosion.

2. MEASUREMENT PROCEDURE AND EXPERIMENTAL RESULTS

The electric explosion was produced by discharging a high-voltage capacitor through the wire. A diagram of the explosion circuit and a description of the oscillography procedure and of the construction of the "current-measuring resistor" are given in Ref. 6.

This investigation concerns primarily copper wires, for it is in this case that the principal features of electric explosions become most pronounced. The wires were 60 mm long and 0.05, 0.1 and 0.15 mm in diameter. Approximately these dimensions are the most frequently encountered in investigations of this type. Experiments were made with a 2.5 microfarad bank of capacitors at initial voltages U_0 ranging from 5 to 40 kv and at two values of the total inductance of the explosion circuit, 0.4 and 4.2 microhenries. Two corresponding groups of oscillograms are given in Figs. 1 and 2. These oscillograms show that as U_0 increases, or as L decreases, the first current pulse that causes the electric explosion of the wire becomes shorter and taller. At relatively low values of U_0, the first current pulse in the explosion circuit is followed by a discharge "pause," which frequently ends in a more powerful current pulse. There is no discharge pause at high values of U_0 and the current again starts increasing after reaching a certain nonzero minimum. Analogous oscillograms are obtained for other size wires.

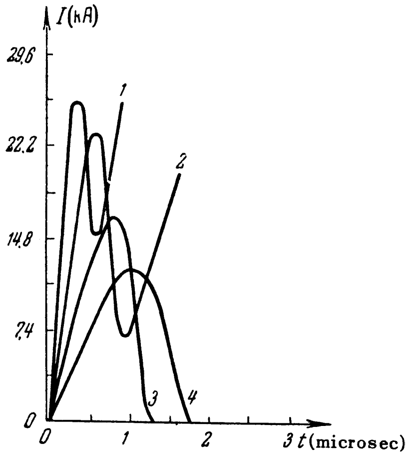

FIG. 1. Current oscillograms, obtained in an explosion of copper wires 60 mm long and 0.15 mm in diameter. Explosion-circuit inductance $L = 0.4 \times 10^{-6}$ henry. Oscillograms *1, 2, 3, 4* correspond to capacitor voltage of 35, 25, 15 and 10 kv. T – time, I – current.

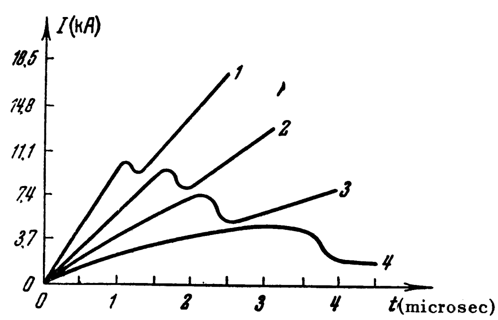

FIG. 2. Current oscillograms for the same wires as in Fig. 1 at $L = 4.2 \times 10^{-6}$ henry. Oscillograms *1, 2, 3, 4* correspond to values of U_0 = 40, 30, 20 and 10 kv.

Figure 3 shows two current oscillograms that illustrate the role of the inductive distortion of the oscillograms in the calculation of the explosion energy. Curve *1* was obtained with the "current-measuring resistor" connected as usual in the oscillograph circuit, while curve *2* was obtained with this resistor connected noninductively*. Curve *3* represents the difference of these two curves and evidently shows the approximate behavior of the inductive voltage drop across the "current-measuring resistor," while curve *2* shows the purely resistive drop, proportional to the explosion circuit. As could be expected, curve *1* of these oscillograms intersects curve *2* at the maximum of the latter where $dI/dt = 0$. It follows from the curves that the inductive voltage drop is comparable with the resistive drop, even exceeding it considerably in the initial portion, and it is therefore evident that the use of the upper oscillogram for energy calculation results in energy values that are much too high.

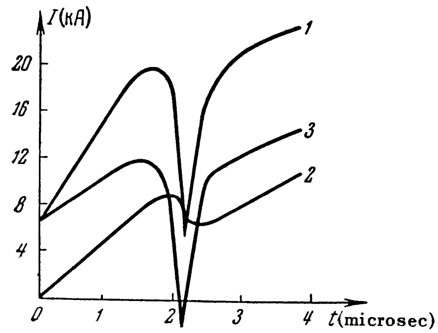

FIG. 3. Oscillograms illustrating the role of inductive distortion.

We start the wire energy calculation with the current oscillogram. Knowing the explosion-circuit parameters and the initial capacitor voltage, we can calculate the energy E_t delivered to the wire within the time t elapsed since the start of the discharge. During this time, the capacitor supplies an amount of energy

$$E(t) = (C/2)[U_0^2 - (U_0 - \Delta U)^2] \qquad (1)$$

$$= U_0 \Delta Q - \Delta Q^2/2C,$$

* The inductance for curve *1* is somewhat different from that for curve *2*.

where U_0 is the initial capacitor voltage, ΔU is the decrease in this voltage during the time t, and $\Delta Q = C\,\Delta U$ is the discharge from the capacitor during the same time. ΔQ can be calculated from the current oscillogram using the following equation:

$$\Delta Q = \int_0^t I(t)\,dt,$$

where $I(t)$ is the value of the current at the instant t, also determined from the current oscillogram. Knowing U_0, C and ΔQ we obtain $E(t)$ from Eq. (1). However, not all of $E(t)$ is liberated in the wire. Neglecting, in view of the short duration of the process, the energy lost through thermal radiation, electromagnetic radiation of the explosion circuit, etc., we can assume that part of the energy $E(t)$ in the wire is in the form of Joule heat E_t and the remaining part is in the form of the energy of the magnetic field produced by the current*. The latter can be calculated from the well-known equation

$$E_m = LI^2(t)/2,$$

where L is determined from the expression for the period of the damped oscillations of the explosion circuit. Knowing $E(t)$ and E_m, we can calculate E_t as the difference

$$E_t = E(t) - E_m. \qquad (2)$$

The oscillograms obtained make it possible to determine the values of the current with an accuracy to 2-3%. The measurement accuracy of U_0, L and C are of the same order, and E_t can therefore be determined with an accuracy to not less than 4-6%. Figure 4 shows curves of the energy delivered to the wire by the time the current reaches its first maximum relative to the capacitor voltage U_0.
Dashes A_1 and A_2 parallel to the abscissa show the values of energy, obtained from tabular data, required to melt wires 0.1 and 0.15 mm in diameter by heating from room temperature. Markers P_1 and P_2 give the energy required for total evaporation of these wires under the same conditions. We restrict ourselves only to the calculation of E_t for the first current maximum, for by the instant the maximum occurs all the remaining capacitor voltage is across the ohmic resistance of the wire making it possible to calculate the value of this resistance with sufficient accuracy without needing to allow for the inductive voltage drop in the explosion circuit. It must be noted that our oscillograms show that the rate at which the current increases, dI/dt, remains constant at relatively large values of U_0 (> 10 kv) from the start of the discharge almost up to the occurrence of the first maximum. It follows from this that in this region the ohmic resistance of the wire is much smaller than the surge resistance of the tuned circuit, and its value cannot readily be computed with any accuracy. It is only near the current maximum that the wire resistance begins to increase rapidly, continuing to increase also beyond the current maximum (see also the curves of Fig. 3 in Ref. 6, obtained for copper wires at relatively low voltages). It follows that near the current maximum the rate at which the energy is liberated begins to increase very rapidly leading eventually to a rapid increase in the wire resistance and to formation of a discharge pause.

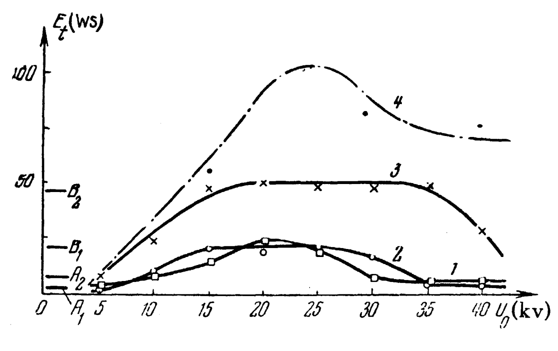

FIG. 4. Curves showing the dependence of E_t on the capacitor voltage. Wire diameter is 0.10 mm in curves *1* and *2* and 0.15 in curves *3* and *4*; L is 0.4×10^{-6} henry for curves 1 and 4 and 4.2×10^{-6} henry for curves *2* and *3*.

The curves of Fig. 4 show that E_t does not increase monotonically with U_0, as expected, but begins to diminish upon reaching a certain maximum that either exceeds or approximates the energy of total evaporation of the wire. If the explosion circuit inductance is high, these curves exhibit a wide plateau, where E_t does not vary with E_0 (curves *2* and *3*). At low values of U_0 (less than 5 kv) E_t approaches the energy needed to melt the

* The resistance of the remaining portion of the explosion circuit is assumed negligible compared with that of the wire. Evidently the estimate of the energy supplied to the wire is somewhat exaggerated here. An estimate based on the attenuation decrement of the circuit shows that this exaggeration does not exceed 10-15%, and therefore does not affect the deductions substantially.

corresponding wire, in agreement with our data[6] and in contradiction with the data of Refs. 3-5. One can therefore conclude from examination of the curves in Fig. 4 that the start of the processes leading to the discharge pause does not depend on the energy delivered to the wire alone, but also on the value and duration of the current.

The curves of Fig. 5 show the dependence of the wire resistance for the maximum of the first current pulse, $R_m = (U_0 - \Delta U)/I_m$, on the initial capacitor voltage U_0. Curves *1, 2, 3* and *4* correspond to curves *1, 2, 3* and *4* of Fig. 4. They show that R_m increases with U_0 for identical wires. For the same value of U_0 and for the same wire, R_m increases with the inductance L. This apparently is due to the increased duration of the current at large values of L. It follows from comparison of the curves of Figs. 4 and 5 that the value of R_m is not determined uniquely by the amount of energy as supplied, but is also a function of I_m and τ_m, where τ_m is the time interval from the start of the discharge to the occurrence of the first current maximum; this interval characterizes the time of action of the current. It is evident from examination of the current oscillogram that the wire resistance behaves analogously near the maximum of the first current pulse and to the right of it up to the following current minimum, where if there is no discharge pause, the resistance assumes a maximum value and then drops sharply to a very small value owing to the wire "breakdown;" if a discharge pause occurs, the resistance continues to increase and tends to infinity.

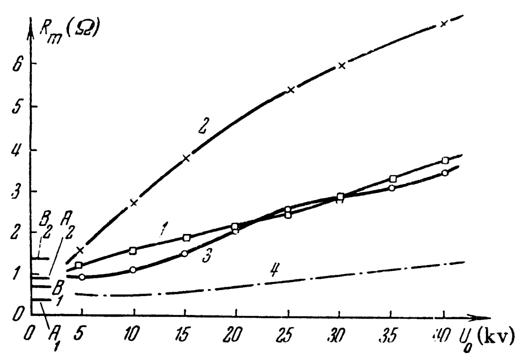

FIG. 5. Dependence of wire resistance R_m at the instant of the maximum of the first current pulse on the capacitor voltage.

Markers A_1, A_2, B_1 and B_2 on Fig. 5 correspond to the tabular values of copper wire resistance: A_1 and A_2 give the resistances of 0.15 and 0.1 mm diameter wires just below their melting point, and B_1 and B_2 give the resistances of the same wire towards the end of their melting. Comparing these resistances with the values R_m obtained from the curves of Fig. 5, we see that at low values of U_0 (approximately 5 kv) R_m assumes values that are comparable with the above data. At higher values of U_0, the value of R_m exceeds considerably the resistance corresponding to the fully melted wire.

Figure 6 gives curves of τ_m vs. U_0. Curves *1, 2, 3* and *4* correspond to curves *1, 2, 3* and *4* of Fig. 4. They show that as U_0 increases, the value of τ_m diminishes at all times for all wire diameters and for all values of the inductance L. At high values of U_0 the rate at which τ_m decreases is constant, while the rate at which I_m increases tends to zero (see oscillograms and also curves of Fig. 7).

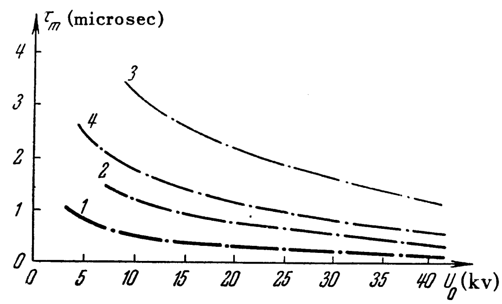

FIG. 6. Curves showing τ_m vs. capacitor voltage.

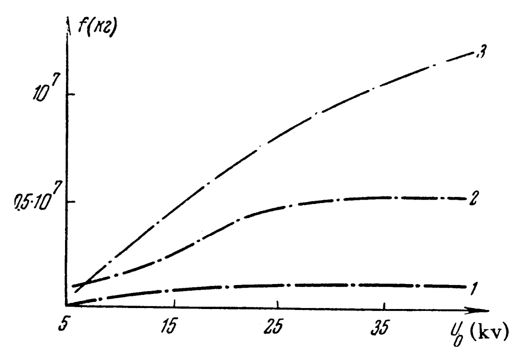

FIG. 7. Dependence of the force compressing the wire on the initial capacitor voltage. Curves *1, 2* and *3* correspond to wire diameters of 0.05, 0.10 and 0.15 mm.

3. EVALUATION OF RESULTS

It is possible to conclude from the data given that at high capacitor voltages the resistance of a wire in electric explosion is not uniquely determined by the energy supplied to it. It follows from a comparison of the curves of Figs. 4 and 5 that under certain experimental conditions (low inductance in the explosion circuit) the wire absorbs more energy and has less resistance, while under other conditions (greater inductance in explosion circuit) it absorbs less energy and has a higher resistance. The resistances may differ by a factor of several times for the same value of voltage and for identical wires. It appears to us, in agreement with Ref. 11, that such large resistance variations cannot be explained with the aid of any electronic mechanism whatever. It is most sensible, apparently, to admit the existence of energy leakage from the wire during the explosion process itself, this leakage depending on the discharge conditions. The apparent "excess energy" could then be attributed to this leakage. Careful examination of the electric-explosion process makes it possible to ascertain whether such energy leakage exists.

In fact, according to the explanation of the electric explosion given in Ref. 10, the characteristic feature of the explosion is its irregularity, or more accurately, its periodicity in space. Shadow photographs given in that reference show that at a certain stage of development the wire explosion breaks up into a large number of separate "micro-explosions," which are distributed approximately periodically along the wire and which occur simultaneously over the entire length of the wire. Upon further development, the micro-explosions merge into one overall explosion. The total power of the micro-explosions is considerably greater than the average wire-explosion power in view of their short duration and in view of the fact that they liberate a large amount of energy, and therefore, as the same photographs show, the products of the micro-explosions, having a higher velocity, penetrate deeper into the surrounding medium (air) than the main mass of explosion products that follows them. It is evident that the dispersion of the micro-explosion products is associated with consumption of a certain portion of the capacitor energy, which indeed determines, in our opinion, the "excess energy" in the wire.

It is possible to estimate approximately the "excess energy" from the spatial periodicity of the explosion process and from experiments made with wire explosions in vacuum. Shadow photographs[10] illustrating the periodicity and the radial stratification of the explosion show that the mass expelled by the micro-explosions does not exceed approximately one-tenth of the total mass of the wire. The mass of a wire 0.15 mm in diameter and 16 mm long is approximately 10^{-2} gm. Consequently, the "excess energy" should be carried away by a mass approximately 10^{-3} gm. It is impossible to determine the "excess energy" from the curves of Figs. 4 and 5, for the increased resistance of the wire may be due either to the heating and partial evaporation*, or to the dispersion of the still-unevaporated portions of the wire under the influence of the shock waves that propagate from the centers of the micro-explosions[10]. One can estimate, however, the upper limit of the "excess energy" in the case, for example, of curve *4* of Fig. 4, to be approximately several tens of Joules. Let us assume that this limit for the maximum of the curve is 100 J or 10^9 erg. Then, if all this energy is converted into the kinetic energy of the expelled mass, the approximate velocity of this mass should be 10^6 cm/sec. Experiments made in a vacuum chamber with a ballistic pendulum have shown that with 40 kv across the capacitor the average escape velocity of the explosion products from the wire reaches 2×10^5 cm/sec, and when the voltage is decreased to 20 kv the escape velocity decreases to 10^5 cm/sec. Taking into account the statements made earlier about the micro-explosion power, one must assume that the escape velocity of the micro-explosion products should be considerably greater than the escape velocity of all the explosion products. In addition, we know that when a wire explodes in vacuum it is shunted by the arc discharge that is produced in the metal vapor, and this should evidently result in a lower micro-explosion energy in vacuum compared with micro-explosions in air, where no shunting or wire "breakdown" is observed up to the first current maximum. Under the conditions in which a wire explodes in air an escape

* We have in mind here not the evaporation of the wire at the sites of the micro-explosions, but the evaporation of the remaining parts, for the micro-explosion sections are strongly heated and enveloped by low-resistance arcs, thus not affecting noticeably the overall resistance of the wire.

velocity of approximately 10^6 cm/sec for the micro-explosion products appears quite reasonable, and the energy carried away in this case is quantitatively quite adequate to account for the "anomalous" behavior of the resistance described above. No difficult-to-explain anomalies are thus encountered with respect to the relationship between the wire resistance and the amount of energy supplied even if the current density is approximately 10^8 a/cm^2 (the maximum current density for a wire 0.15 mm diameter at $U_0 = 40$ kv is 1.6×10^8 a/sq.-cm). It would be interesting to determine quantitatively, from the curves of Figs. 4 and 5, the behavior of the "excess energy" as a function of U_0, but we are not in a position to do so, owing to the complexity of the processes leading to the increase in the wire resistance near the current maximum. Not knowing the amount of energy remaining in the wire, we can nevertheless assume that R_m will be proportional to the amount of this energy. It is then clear from the curves of Figs. 4 and 5 that the behavior of the "excess energy" as a function of the behavior of E_t should be qualitatively characterized by the presence of a maximum. In order to understand such a behavior of the "excess energy", let us turn to Figs. 6 and 7. Figure 7 shows curves for the voltage vs. the force that compresses the wire in a radial direction and that is caused by the magnetic field. This force can be expressed by the well-known equation[12]

$$f = \sigma j^2,$$

where f is the force acting on unit volume of wire carrying current on its periphery, σ is the circumference of the wire section, and j is the current density; f is given in dynes if σ is given in centimeters and j in electromagnetic current units. It is evident from these curves that f varies over a wide range and becomes large enough to compress the liquid portions of the wire for a very short time. This compression indeed causes micro-explosions in accordance with the mechanism suggested in Ref. 10 for the electric explosion. Assuming that f is either constant or increases slowly at high capacitor voltages, one can conclude that the micro-explosion energy will be determined by the time of action of this force. Quantitatively, this energy is roughly the square of the momentum $(f\tau_m)^2$. Calculations of this product, based on the data of Figs. 6 and 7, show that the behavior of $(f\tau_m)^2$ as a function of the voltage across the capacitor is analogous to the behavior of the "excess energy" described above. This confirms the assumption made above that energy leakage causes the "anomalous" behavior of the resistance during the electric explosion of the wire.

An assumption was stated in Ref. 10 that the action of the magnetic field on the wire imposes an upper limit on the current density attainable in an electric explosion. The oscillograms obtained show that for small-diameter wires (0.1 mm and below) such a limit indeed exists and equals approximately 10^8 a/cm^2 (see Fig. 7). It follows from the same oscillograms that increasing the wire diameter and using a voltage source of sufficient energy increases the attainable current densities, although slowly. One must evidently seek in this direction a possible path for obtaining higher current densities.

4. CONCLUSIONS

1. The experiments described above have established that at relatively low capacitor voltages the electric explosion produces during the time interval from the start of the discharge to the first current maximum no anomalies in the relationship between the energy supplied and the wire resistance, at least for copper wire.

2. At high capacitor voltages, to the contrary, the resistance of the wire exhibits an absence of a unique relationship between the energy liberated, even within these limits; this is attributed to energy leakage from the wire during the explosion process.

3. The compressing action of the magnetic field of the current in the electric explosion limits attainable values of current density, particularly in the case of thin wires. As the wire diameter increases, the attainable current densities also increase.

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[1] A. A. Ignat'eva and S. G. Kalashnikov, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 385 (1952).

[2] E. S. Borovik, Dokl. Akad. Nauk SSSR **91**, 771 (1953).

[3] S. V. Lebedev and S. E. Khaikin, J. Exptl. Theoret. Phys. (U.S.S.R.) **26**, 629, 723 (1954).

[4] S. V. Lebedev, J. Exptl. Theoret. Phys. (U.S.S.R.) **27**, 487, 605 (1954).

[5] L. N. Borodovskaia and S. V. Lebedev, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 96 (1955); Soviet Phys. JETP **1**, 71 (1955).

[6] Bondarenko, Kvartskhava, Pliutto and Chernov, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 191 (1955); Soviet Phys. JETP **1**, 221 (1955).

[7] W. M. Conn, Phys. Rev. **79**, 213 (1950); J. Opt. Soc. Am. **41**, 445 (1951); Nature (London) **169**, 1950 (1952; Phys. Rev. **98**, 1551 (1955).

[8] B. Eiselt, Z. Physik **132**, 54 (1952).

[9] J. Wrana, Arch. Elektrotech. **33**, 656 (1938).

[10] Kvartskhava, Pliutto, Chernov and Bondarenko, J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 42 (1956); Soviet Phys. JETP **3**, 40 (1956).

[11] V. L. Ginzburg and V. P. Shabanskii, Dokl. Akad. Nauk SSSR **100**, 445 (1955).

[12] E. F. Russ, J. Tech. Phys. **12**, 529 (1930).

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The Ionization Spectrum of Cosmic Rays 3250 m above Sea Level

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Using a previously described method,[1] we measured the ionization spectra produced by the soft and hard components of cosmic rays of various ranges at 3250 m above sea level. The proton momentum spectrum was obtained in the interval 0.36–1.0 bev/c.

IN an earlier paper,[1] we described in detail a method for measuring the ionization spectrum of cosmic rays. The basic idea of the method is to select the minimum ionization produced by a particle as it passes through several scintillation crystals; experiments at sea level showed that quantitative information about the proton component of cosmic rays with ranges 2 to 15 cm of lead could be obtained.

It was interesting to apply this method to the ionization spectra of cosmic rays at mountain altitudes, especially as the resolving power of our system was considerably better than that available to previous authors.[2,3] With this in mind, the apparatus was transported to the Alagez high altitude (3250 m above sea level) station of the Academy of Sciences of the Armenian SSR.

Two series of measurements were made. In the first series, lasting 407 hours, we measured the ionization spectrum of particles having ranges 2–3, 3–5, 5–9 and 9–15 cm of lead. In the second series, which lasted 270 hours, the lead filters were replaced by carbon ones equivalent to 1–1.5, 1.5–2, and 2–3 cm of lead. During both series, the ionization spectrum of particles with ranges in excess of 15 cm of lead was also measured.

The amount of material above the apparatus was kept to a minimum and consisted of a single layer of iron roofing plus 0.5 cm plywood. During both series of measurements (i.e., for ranges 2 to 15 cm of lead) we counted the number of times two or more particles went through the system together (multiple traversals). In analyzing the data, these multiple traversals were discarded, so that our results for the soft component refer to single particles only. Multiple traversals in the hard component were not registered.

Figure 1 shows the ionization spectrum obtained for the hard component (particles with ranges of more than 15 cm of lead); from it we can obtain the resolving power of our system. Ionization in arbitrary units is plotted along the abscissa, and the relative intensity in some ionization interval along the ordinate. Our method[1] is such that the ionization spectrum shown in Fig. 1, together with all the other spectra presented in this paper, is the product of the differential distribution of ionization and the fourth power of the integral distribution. The curve in the figure is almost symmetric and has one sharp maximum. The relative width at half maximum is 18%.

Seven ionization spectra for particles of various ranges in the soft component were taken. As an example of these, Fig. 2 gives the spectrum corresponding to 1–1.5 cm of lead. The insert shows the right-hand side of the spectrum on an enlarged scale. In this graph ionization is measured in units of the minimal ionization, which is taken to be the ionization at the maximum in the spectrum corresponding to the hard component. The arrows show the most probable ionization Δ_0 for μ-mesons, protons and mesons of masses 550 and 965 electron masses. The other 6 ionization spectra for the