SOVIET PHYSICS JETP VOLUME 5, NUMBER 4 NOVEMBER, 1957

Investigation of the Penetrating Component of Electron-Nuclear Showers by the Delayed Coincidence Method in Conjunction with a Hodoscope

G. B. ZHDANOV AND A. A. KHAIDAROV
"Nigrizoloto" Scientific Research Institute
of the Ministry of Non-ferrous Metals

(Submitted to JETP editor November 27, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 706-713 (April, 1957)

The distribution in range of slow mesons created by cosmic rays on lead and graphite nuclei at effective energies on the order of 5 Bev and higher has been investigated by a method described in Ref. 1. Some peculiarities of secondary interactions of penetrating particles of electron-nuclear showers at the same energies are also examined.

1. INTRODUCTION

WE HAVE CARRIED OUT, at an altitude of 3860 m above sea level, experiments investigating the energy spectrum of slow π^+-mesons generated in electron-nuclear showers. We used the method of delayed coincidences in conjunction with a hodoscope.

The present article gives the basic results obtained. A study of the generation of comparatively slow mesons during nuclear interactions of cosmic ray particles with matter was carried out for primary particles in an average energy range of ~5 Bev or higher. The experimental method used has been set forth in detail in Ref. 1 and partially in Ref. 2. Schematic diagrams of the apparatus used in the present work are given in Figs. 1 and 2.

Let us carry out the analysis of the experimental data which is involved in the classification of the phenomena registered by the apparatus. Analyzing the hodoscope photographs, we may divide all the showers into several types according to the following characteristics: 1) a double δ-shower, the criterion for which is the presence of operated counters only among the directing group $M1$ and $M2$ and only in immediate proximity to each other; 2) showers with air accompaniment, among which we include events where at least one charged particle has passed through a group of counters located 2-3 m to one side of the main apparatus; 3) showers accompanied by the operation of several counters placed over the main apparatus, but without having a charged particle go to the side group of counters, have been conditionally classified as narrow showers; 4) all the remaining showers have either been included in the group of electron-nuclear showers or else have been put in the category of cases difficult to interpret if the picture observed in the hodoscope could not be explained as a nuclear interaction in the layer of material between counters $M1$ and $M2$. Cases of secondary interaction (produced by a radioactive particle belonging to a registered shower) in the hodoscope may be recognized during visual analysis of the hodoscope photographs. The distribution of the showers according to the different categories with various filters present in the apparatus is given in the table.

The first and second lines of the table give the data relative to sparse ($n \leqslant 3$) and dense ($n \geqslant 4$) electron-nuclear showers, while the third line gives data relative to electron-nuclear showers with secondary interactions a) from charged shower particles, b) from neutral shower particles. The fourth and fifth lines give the number of sparse double δ-showers and dense double δ-showers (the density being estimated from the number of activated counters). The sixth and seventh lines give the number of narrow and extensive air showers, and, finally, the eighth line gives the cases that are difficult to interpret.

An analysis of the results given in the table shows that it is possible to collect a great deal of experimental material by means of the present method.

If they are related to the corresponding nuclear ranges, the numbers of electron-nuclear showers produced in the Pb and C filters per time unit are experimentally equal and amount to ~9 per hour (for dense showers). This shows that these filters are not essentially different in their effectiveness in registering such showers.

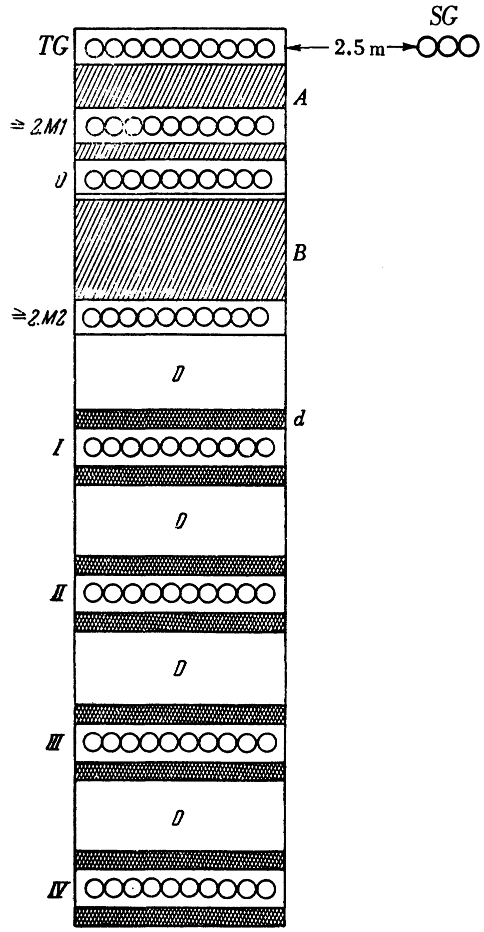

FIG. 1

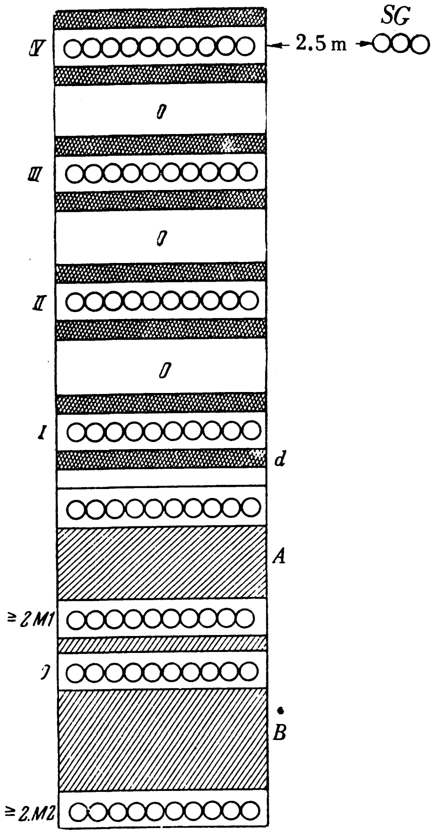

FIG. 2

FIG. 1. Arrangement of counters and filters in the apparatus (basic variant). *TG*—top group of counters; *SG*—side group of counters (for recording wide showers); *M*1—upper directing group; *M*2—lower directing group (all the indicated counters are connected to an ordinary hodoscope of type GK-3, groups *M*1 and *M*2 separate out the cases where ⩾ 2 particles pass through); 0—IV are rows of counters connected to the double screen of a hodoscope of type GK-5; *A* is an interchangeable filter (Pb and C) in which the showers under investigation are generated; *B* and *D* are interchangeable filters (Pb or Fe) which determine the ranges of the mesons registered by the counter trays of the type GK-5 hodoscope; the filters *d* are fixed filters (of 2.5 cm thickness) which are sources of the decay electrons. The working dimensions of all the counters are 33 × 300 mm.

FIG. 2. Arrangement of counters and filters in the experiment for the study of the vertical return current. The designations are the same as in Fig. 1.

2. SECONDARY INTERACTIONS IN SHOWERS

The currents of neutral and charged radioactive particles produced in electron-nuclear showers have been compared for the configuration of counters shown in Fig. 1. We determined these currents by means of the number of secondary nuclear interactions in the filters of the hodoscope. In 220 hours of measurements with iron filters of total thickness 160 g/cm² present in the hodoscope, 260 cases of secondary nuclear interactions from nuclear particles were obtained. If we also take into account the presence of neutrons which do not interact in passing through the filters (assuming the interaction cross section to equal the geometric ones) the total flux of fast neutrons becomes $N_0 = (6 \pm 0.65)$ hr^{-1}. Relative to a single electron-nuclear shower, this number amounts to $n_N = (0.2 \pm 0.025)$. Reasoning in an analogous manner about the interactions with charged particles, after the exclusion of δ-showers, we obtain $N_0 = (16.8 \pm 1.2)$ hr^{-1} and $n_C = (0.62 \pm 0.043)$. Here we use n_N and n_C to indicate the average number of neutral and charged radioactive particles, respectively, in a single shower emitted within the limits of a definite angle with respect to the vertical. Assuming that the

Character of the observed phenomenon	A = 6 cm Pb, d = 2.5 cm Fe						A = 16 cm C, d = 2.5 cm Fe						A = 6 cm Pb, d = 2.5 cm Fe						A = 16 cm C, d = 2.5 cm Fe					
	$D = 0$			D = 8 cm Fe filters			$D = 0$			D = 8 cm Fe filters			$D = 0$			D = 8 cm Fe filters			$D = 0$			D = 8 cm Fe filters		
	ν	s	N	ν	s	N	ν	s	N	ν	s	N	ν	s	N	ν	s	N	ν	s	N	ν	s	N
Group number	1			2			3			4			5			6			7			8		
1. Sparse electron-nuclear showers (number of penetrating particles in the lower row of counters $n \leqq 3$)	17.7	22	369	18	21	340	16	21	334	17	25	409	0.12	28	49	0.16	25	44	0.08	20	20	0.09	22	23
2. Dense electron-nuclear showers (number of penetrating particles $n \geqq 4$)	8.8	11	184	9	11	170	7.9	10	166	8.6	12	207	0.18	42	73	0.26	43	74	0.14	33	33	0.13	30	32
3. Electron-nuclear showers with secondary interactions																								
a) from charged shower particles	2.7	3.3	57	1.84	2.2	35	3.1	4.0	65	1.9	2.7	45	0.012	2.9	5	0.018	2.9	5	0.13	7	7	0.016	3.7	4
b) from neutral shower particles	1.4	1.7	29	1.80	2.1	34	2.6	3.4	55	1.5	2.2	36	0.007	1.7	3	0.021	3.5	6	0.017	4	4	0.02	4.7	5
4. Sparse double δ-showers	24	29	503	25.7	30	488	22.9	30	480	17.5	25	420	0	0	0	0	0	0	0	0	0	0	0	0
5. Dense double δ-showers	6.3	7.7	132	6	7	113	5.0	6.5	106	6.2	8.8	149	0	0	0	0	0	0	0	0	0	0	0	0
6. Narrow air showers	10.3	13	217	10.5	12	191	6.2	8.1	131	5.2	7.5	125	0.06	14	24	0.064	10	18	0.05	12	12	0.044	10	11
7. Extensive air showers	6	7.3	125	6,6	7.8	125	7.7	10	162	7.0	9.1	168	0.015	3.4	6	0.056	9.2	16	0.06	15	15	0.096	22	24
8. Cases difficult to interpret	4.4	5.4	93	6.0	7.1	115	5.6	7.3	118	4.6	6.6	110	0.027	6.3	11	0.035	5.8	10	0.04	9	9	0.032	8	8
General total of all events	1709			1611			1617			1666			174			173			100			107		
Time of measurement (in hours)	21			19			21			24			403			283			237			250		

NOTES. The data of groups 1, 2, 3, and 4 refer to showers without meson decays, while those of groups 5, 6, 7, and 8 refer to showers with meson decays. ν is the event frequency per hour; s is the relative number of events; N is the total number of cases treated.

number of fast protons in electron-nuclear showers is equal to the number of fast neutrons, that is, 0.2, we find the number of π^+-mesons to be ~0.4. The basic result of the given measurements is the following: 0.2 of the particles in a shower consist of fast neutrons (with minimum energy on the order of 0.5 Bev), 0.2 of the particles are protons with the same energy, and 0.4 of the particles are π-mesons. Here all the fluxes are with respect to a comparatively small interval of angle with the vertical and, hence, also with respect to the primary particles.

The intensities obtained for the fluxes of secondary radioactive particles of various kinds agree satisfactorily with the absorption ranges for the radioactive component in air and in dense materials. Actually, it is known that the average ranges for the absorption and interaction of the radioactive component in a material λ_a and λ_0, are connected by the simple relationship

$$1/\lambda_a = (1/\lambda_0)(1-n_g),$$

where n_g is the average number of radioactive particles. If we substitute $\lambda_0 = 60$ g/cm², $\lambda_a = 2\lambda_0$ for air and $\lambda_a = 3\lambda_0$ for dense materials, it turns out that on the average ~0.5 secondary high-energy radioactive particles are generated for each interaction in air, and that all of them must be stable particles, that is, nucleons. For a dense material the number of nucleons turns out to be $\frac{2}{3}$ rather than $\frac{1}{2}$, and unstable radioactive particles, that is, fast mesons, must also be included. Under the actual conditions of our experiments, the energies of the secondary interactions are selected to be much less than those of the primary interactions and, moreover, tertiary interactions are taken into account. All this, when summed up, leads to the conclusion that the total number of secondary radioactive particles in a dense material turns out to be 0.8 instead of the expected $\frac{2}{3}$. In the present instance the definiteness of the results is not great enough to permit their being used except as an order of magnitude.

In order to obtain a comparison of the intensity of the generation of mesons in different materials (C and Pb), the results on the decay of mesons in sparse ($n_s \leqslant 3$) and dense ($n_s > 3$) showers in the different configurations of the experiment were added up (n_s is the number of penetrating particles). During the same time interval 108 and 240 decay events were found in C and Pb, respectively.

These results (taken relative to one hour of measurement) give the following values for the number of mesons decaying in the apparatus: 0.22 ± 0.02 for C and 0.36 ± 0.02 for Pb.

The results obtained show that for generating particles having the same energies ($E_{gen} \sim 5$ Bev) the total number of comparatively slow mesons (with energies up to 800 Mev) generated by them in nuclear acts depends weakly on the atomic number of the nucleus.

3. DETERMINATION OF THE RANGE SPECTRUM OF THE π^+-MESONS

Both variants of the apparatus were used in the measurements (see Figs. 1 and 2). The treatment of the experimental results in determining the spectrum of the meson ranges in the showers was begun with the choice of groups for the meson decays. The place of the decays was determined to an accuracy of the thickness of a single filter. After determining the location of the meson decays on each of the photographs, we were able to unite in a single group all the cases with given range R_i, where $i = 1, 2, 3, \ldots, 8$ is the number of filters located between the points of generation and decay of the meson.

On grouping the direct results of the experiment we obtained the number of decays $N(R_i)$ corresponding to various ranges R_i and for a definite time of measurement. After this, with the aid of special control experiments and statistical methods of treating the hodoscope photographs, we carried out an evaluation of the following effects concerned with the apparatus:

1. Accidental delayed coincidences. The probability of such a "decay" is not greater than one case in 1000 showers for the data used in the calculations.

2. Effect of the occupancy of the counters of the hodoscope rows by prompt shower particles on the registration of mesons (as a result of this effect, mesons decaying at different distances from the place of generation of the shower are registered with different efficiencies).

3. Difference in the "transmission factor" of the different counter rows of the hodoscope. A special control experiment (without filters in the hodoscope) permits the determination of the so-called geometrical factor for each row, that is, the correction factor which takes account both of the difference in the distances of the rows from the point of generation of the shower and of the angular distribution of the shower particles.

Corrections were also applied to the nuclear interactions. These consisted of, first, allowances for the nuclear absorption of π-mesons in the filters of the apparatus (with effective cross section $\sigma = 0.7\,\sigma_{0\,geom}$) and, second, allowances for the secondary generation of π-mesons in these filters by radioactive particles (the number of which amounts to no less than $^2\!/_3$ per shower).

After introducing all these corrections and taking account of the effectiveness of the apparatus in registering the stopped mesons, we obtained the range spectrum of the π^+-mesons generated in C and Pb. The weak dependence of the form of the generated spectra on the nature of the nucleus permits the results obtained for lead and graphite to be combined in order to obtain greater statistical accuracy. The averaged range spectra of the mesons is shown in Fig. 3 for the direct and return vertical fluxes. It should be kept in mind that owing to a certain indefiniteness in the corrections for the secondary nuclear interactions, the form of the spectrum for path lengths exceeding the average range of the nuclear interactions also becomes somewhat indefinite.

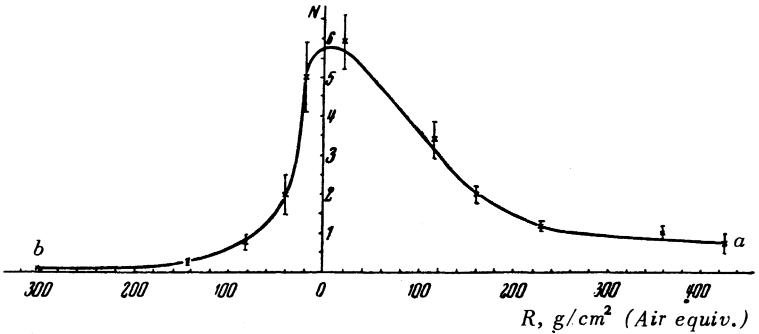

FIG. 3. Average range spectra for the direct and return fluxes of π^+-mesons generated in graphite and lead: a(portion of the curve for $R < 100$)—direct flux, b—return flux

We have compared the spectrum which we have obtained for the ranges of the π^+-mesons in the direct current with the results of other authors[3-5]. A comparison of photographic plate data (for the stratosphere) with the results of our experiments gives (on taking account of secondary interactions) satisfactory agreement, in spite of a considerable difference in the conditions of measurement. Actually, our apparatus recorded showers with higher average energy than in the experiments with photographic plates, owing to the presence of a control system which selected showers for which the number of penetrating particles was not less than two. A comparison with the momentum spectrum obtained at a height of 3200 m by the mass spectrometer method[4] and with the range spectrum obtained by the method of delayed coincidences[5] showed a rather significant deviation from these spectra. This difference is connected primarily with the fact that in the mass spectrometer[5] and in the apparatus used in Ref. 6 the particles studied were generated by nucleons of comparatively small energy, while we chose interactions of higher energy in our apparatus. From the comparison of our results with those referred to, we can conclude that the energy spectrum of slow mesons becomes harder with increasing energy of the generating component. It follows from this that the meson energy spectra studied by different methods depend to a very high degree on the "hardness" of the control system of the apparatus.

The amount of the return current of π^+-mesons in electron-nuclear showers was also determined and found to be 24 ± 7% of the primary current. This result does not contradict (to within the limits of error of the experiment) the photographic plate data.

4. INTENSITY OF GENERATION OF SLOW MESONS FOR DIFFERENT NUCLEAR INTERACTION ENERGIES

To explain how the form of the meson spectrum depends on the average energy of the generating particles, we determined the number of very slow mesons (with range of 20 g/cm² air equivalent) relative to the number of "fast" mesons (that is, mesons decaying in the remaining rows of the hodoscope) as a function of the energy of the electron-nuclear showers. In this determination, the electron-nuclear showers were grouped by energies according to the number of particles in these showers. The results obtained (after applying the corrections for the ap-

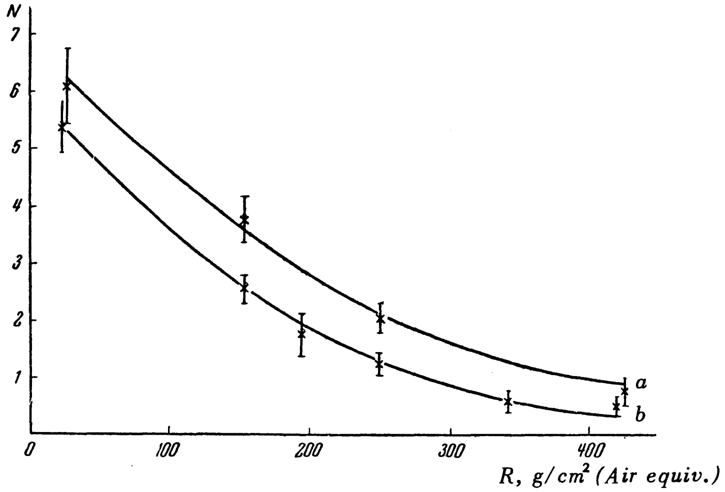

FIG. 4. Meson range distribution curves for showers of different densities: *a*—for dense showers ($n > 3$), *b*—for sparse showers($n \leqslant 3$). *n* is the number of counters triggered (in row *M*2).

paratus) are displayed as curves in Fig. 4. From these curves it may be established that π^+-mesons with ranges of up to 20 g/cm^2 make up as much as 20% of the total number of π^+-mesons for sparse showers ($n \leqslant 3$) and about 15% for denser showers ($n > 3$), with an accuracy of the order of 20% in both estimates.

To clarify the same question, the relative numbers of slow mesons were compared for the cases where the generation of the mesons was accompanied by the passage of an air shower and the cases where the generation of the mesons occurred in the absence of an air shower. The probability of the appearance of a slow π^+-meson (with range of up to 20 g/cm^2) is $(5.8 \pm 1.15) \times 10^{-3}$ in the first case and $(11.6 \pm 0.9) \times 10^{-3}$ in the second. From the experiments of Liubimov *et al.*[6] and Zatsepin *et al.*[7], it follows that the average energy of generating particles accompanied by an air shower is several times greater than the average energy of generating particles not accompanied by such a shower. Analyzing the data given above, we can say that as the energy of the generating particles is increased, the number of slow mesons decreases approximately twice as fast.

This result was double checked. For this purpose while processing the experimental material we selected and set aside data on showers with two or more penetrating particles, the half angle of separation of which was of the order of 15°. In such a case the number of slow mesons relative to a single shower amounted to $(4.4 \pm 1.2) \times 10^{-3}$, while for cases in which the average energies of the generating particles are 3–5 Bev it amounts to $(11.6 \pm 0.9) \times 10^{-3}$. The energy of the generating particles of the shower selected as indicated above is calculated from

$$\cot \theta_{1/2} = \gamma_c = \sqrt{(\gamma_0 + 1)/2}$$

where $\gamma_0 = E_0/Mc^2$, and is of the order of magnitude of 2×10^{10} ev. From the results obtained it is evident that on going over to primary energies of the order 2×10^{10} ev, the number of slow mesons relative to a single shower is smaller by at least a factor of two than the number of such mesons which are observed for particle energies of 3–5 Bev.

From the curves shown in Fig. 4 it is clear that in the interval of ranges up to 100 g/cm^2 the number of mesons depends weakly on the total number of particles in the shower, while for mesons with larger values of range this dependence is stronger, and the total number of mesons increases considerably with the number of particles. A dependence of such a nature is partially explained by secondary generation of slow mesons by shower particles, and not merely by changes in the energy spectrum of the mesons in the act of primary interaction.

If we consider the simplest model of a nucleon-nucleon collision and take account of the fact that the meson distribution is isotropic in the center of mass system, we find that for an energy of the generating particles of the order of 10 Bev the probability of generation of a slow meson (with range ~ 20 g/cm^2) is not greater than 7% (since these mesons emerge at an angle of not less than 150° in the center of mass system). In the experiment this portion amounts to 15–20%. However, the results at our disposal do not yet allow us to decide to what extent such a discrepancy should be attributed to the doubtfulness of the simplest statistical model and to what extent it should be attributed to intranuclear or extranuclear cascade processes.

CONCLUSIONS

1. In the present work the range spectrum for the return component of $\pi^{\pm}$-mesons generated in lead nuclei has been determined and compared with the range spectrum in the direct current. The return meson flux was found to amount to 24 ± 7% of the direct meson flux.
2. It has been established that the number of π^{+}-mesons with a range of the order of 20 g/cm^2 depends weakly on the energy of the generating particles, decreasing somewhat with increase in this energy.
3. It has been shown that for measured energies of the generating particles (not higher than 5 Bev) the number of slow mesons formed also depends weakly on the atomic number of the nucleus.

---

[1] G. B. Zhdanov, J. Exper. Theoret. Phys. (U.S.S.R.) **30**, 437 (1956), Soviet Physics JETP, **3**, 323 (1956).

[2] A. A. Abdullaev, G. B. Zhdanov, L. N. Korablev, A. A. Khaidarov, J. Exper. Theoret. Phys. (U.S.S.R.) **21**, 1072 (1951).

[3] U. Camerini *et al.*, Phil. Mag. **42**, 1241 (1951).

[4] V. Kamalian and A. Alikhanian, Doklady Akad. Nauk SSSR **97**, 425 (1954).

[5] A. A. Abdullaev, Dissertation, Moscow, Physical Institute of the Academy of Sciences, 1954.

[6] Korablev, Liubimov and Nevraev, Doklady Akad. Nauk SSSR **68**, 273 (1949).

[7] Anishchenko, Zatsepin, Rosental' and Sarycheva, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 143 (1952).

Translated by M. J. Gibbons
167

SOVIET PHYSICS JETP VOLUME 5, NUMBER 4 NOVEMBER, 1957

Measurement of High Temperatures in Strong Shock Waves in Gases

I. SH. MODEL'
Institute of Chemical Physics, Academy of Sciences SSSR

(Submitted to JETP editor, November 30, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 714-726 (April, 1957)

A photographic method for the measurement of high temperatures and the absorption coefficient of radiation by the gases in a plane shock wave is described. Results of the measurement of the temperature and absorption coefficient of a plane shock wave in air are presented for wave velocities between 6.4 and 8 km/sec. In strong shock waves in heavy inert gases the experimentally measured temperatures are much lower than the calculated values. It is suggested that this phenomenon is due to screening of the shock wave front by a layer of gas heated by radiation from the shock front.

INTRODUCTION

DURING THE PAST FEW YEARS, methods have been developed to obtain powerful shock waves using explosives. Calculated temperatures up to 70000 °K at pressures of the order of 10^4 kg/cm^2 may be obtained in the wave front by propagating such shock waves is argon ($p_0 = 1$ kg/cm^2, $T_0 = 273$ °K). In spite of the difficulties associated with explosion experiments, the investigation of of strong shock waves is of great interest for the study of the properties of gases at such high temperatures and pressures.

At the present time, many perfected techniques and instruments are available in experimental gas dynamics for the investigation of rapidly-occurring processes. However, comparatively little attention has been paid to the development of methods of temperature measurement. Most of the work devoted to the luminosity of gases in a shock wave has been