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COSMIC RADIATION AND NEGATIVE PROTONS

BY

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Introduction.

The three main problems, still unsolved, in the domain of cosmic ray physics are at present the following:

(a) What is the origin of the enormous energies revealed experimentally in cosmic radiation?

(b) Of what particles does the primary component hitting the top of the atmosphere consist?

(c) How is the genesis of the various components observed in the atmosphere, at sea level and at great depths?

Although much thought has been devoted to the first problem, its final solution has not yet been definitely found. We shall return to it at the end of this discussion. Regarding the second question, it was until recently generally assumed[1] that the primary radiation consists exclusively of electrons,[2] the positons being slightly more numerous than the negatons. The third question was answered by assuming the soft component, known experimentally to consist of electrons and photons, to be produced directly by cascade multiplication from the primary electrons. Next, the hard component, known experimentally to consist of mesons, was assumed to be produced as a secondary radiation by the photons of the soft component in the upper part of the atmosphere. On the other hand, the hard component also gives rise to a secondary soft component, constituting most of the soft component found at sea level, partly by the radioactive decay of the mesons into electrons and neutrinos, partly by their electromagnetic interaction with the atoms in the atmosphere giving rise to knock-on electrons and brems-

[1] Cf. e. g. the survey in Euler and Heisenberg (1938).

[2] This term we shall use as a generic term for both the positive and the negative particles, which we shall denote as positons and negatons, respectively. (The terms positrons and negatrons often used are incorrect, as the r belongs to the Greek word for amber and not to the ending -on).

strahlung. Besides the mesons the hard component is known experimentally to contain a very small fraction of protons and neutrons, which are assumed to be produced as secondaries from the stars of Blau and Wambacher. These stars are assumed to be nuclear explosion or evaporation processes produced by the absorption of the photons of the soft component. Finally, it has been suggested that the effects at great depths below the surface of the earth may perhaps be interpreted as being due to the hypothetical neutrinos.[1]

In view of the experimental evidence of recent years, however, this picture of the genesis of the various components now seems to be untenable. We shall here first (part 1) try to give a survey of the experimental facts bearing upon our questions (b) and (c). Next, we shall discuss the various possibilities of giving a picture of the genesis compatible with all these data (part 2), thereby discussing (part 3) some arguments in favour of quite a new hypothesis on the existence of *negative protons* in the primary cosmic radiation, which has been put forward independently in two papers by Klein and the author.[2] In the discussion of Klein's paper (part 4) we shall return to the question of the origin of cosmic radiation.

Part 1. Survey of the present experimental data.

Let us briefly summarize what seems to be known at present of experimental facts bearing upon our questions (b) and (c).

(I) *Intensities at sea level.*

First of all, the experimental intensities at sea level:

soft component = electrons + photons (i. e. that part which is absorbed in 10 cm Pb) $\sim$ 23 % of the total intensity;[3]

hard component = mesons (i. e. that part which is not absorbed in 10 cm Pb) $\sim$ 77 % of the total intensity;

total intensity $\sim$ 1-2 particles per cm^2 per min;

[1] Heisenberg (1943) p. 10.

[2] Klein (1945), Arley (1944).

[3] Heisenberg (1934) p. 90: soft component = $Z + W + R \sim 29$ % of hard component, i. e. soft $\sim$ 23 % of total (cf. [1] p. 30).

Johnson (1938) p. 208.

protons ~ fast neutrons ~ $\frac{1}{10}$ particle per cm^2 per day[1] ~ 0·01% of the total intensity;

neutrinos: both existence and, therefore, also intensity quite unknown.

(II) *Latitude effect at sea level.*

Next, we give the experimental data of the geomagnetic effects showing that the primary component consists, at any rate to a certain part, of *charged* particles. The cause of these effects is that the paths of charged particles are bent in the magnetic field of the earth. In order to pass through this field the particles must have a certain minimum energy depending on latitude, incident direction and, to a smaller extent, on longitude due to the magnetic dipole representing the magnetic field of the earth being placed excentrically inside the earth. The theory of these effects has been given by STØRMER, LEMAÎTRE, VALLARTA, and others.[2] The most important of these effects is the *latitude effect* defined as

$$l = \frac{I_{50} - I_0}{I_{50}}, \qquad (1)$$

in which I_{50} and I_0 are the intensities at 50° and 0° geomagnetic latitude (the total intensity being constant at all altitudes above 50° N or below 50° S[3]). The latitude effect depends on the altitude and may be measured for the total radiation or for the hard and the soft components separately. It is, of course, the two last mentioned effects which are of greatest interest. For the *soft component* it is measured by means of G-M-counters, e.g. 3 counters in triangular position covered with 1-2 cm Pb, thus giving the intensity for showers only. The values found by various authors at sea level lie between $l = 0\%$ and $l = 6\%$[4] as compared with values from 14 to 20% for the vertical total.

[1] For the protons: STETTER and WAMBACHER (1939) (quoted in HEISENBERG (1943) p. 121). For the neutrons: FÜNFER (1937), (1938), KORFF (1939), SCHOPPER (1939) (quoted in HEISENBERG (1943) p. 121 and 130).

[2] Cf. e. g. the review of this theory (together with the literature in question) in JOHNSON (1938), BRADDICK (1939) or HEISENBERG (1943).

[3] COSYNS (1936), CARMICHAEL and DYMOND (1937), COMPTON and TURNER (1937).

[4] JOHNSON (1935), PICKERING (1936), JOHNSON and READ (1937), NEHER and PICKERING (1938). (Also quoted in JOHNSON (1938) p. 226).

radiation at sea level measured with the same counters placed in line. If the latitude effect of the total radiation is measured not by counters, but by ionization chambers, the effect turns out somewhat smaller, viz. 8-12 % depending on the longitude;[1] for the chambers measure the intensity from all directions, the counters only the vertical intensity. Taking the rather large statistical fluctuations into account, we conclude with JOHNSON (1938) that

the soft component, = shower producing radiation, shows practically no latitude effect at sea level.

We note that, firstly, it is not quite certain whether the intensity of the shower producing radiation may be put proportional to the intensity of the soft component itself, as this component may also contain some slow electrons which are unable to produce showers in the 1-2 cm Pb placed above the counters. Secondly, also some mesons of the hard component may produce showers. It seems, however, generally agreed in the literature that neither of these two objections need be considered.

In spite of the above mentioned experiments it is stated by HEISENBERG[2] that the soft and the total radiation at sea level, i. e. practically the soft and the hard component, have the same latitude effect ~ 10 %. The reason for this false statement is certainly, as we have already previously pointed out,[3] that HEISENBERG bases his conclusion only on the experiment of AUGER.[4] From this experiment it is, however, impossible to draw any positive conclusions as to the latitude effect of the *soft* component, partly because of the very large fluctuations, partly because the effect for the soft component is here measured by a difference method (vertical intensity in 3 G-M-counters placed in line with and without 20 cm Pb in between). Due to the soft component at sea level contributing only a small fraction of the total intensity (~ 23 %), its contribution to the latitude effect is also small compared with that of the hard component: from (1) we have

[1] COMPTON and TURNER (1937).

[2] Both in the reports of EULER and HEISENBERG (1938) p. 38 and of HEISENBERG (1943) p. 87.

[3] ARLEY and ERIKSEN (1940) p. 20.

[4] AUGER and LEPRINCE-RINGUET (1934). As a curiosity we may mention that HEITLER (1937) draws exactly the opposite conclusion from this same experiment, viz. that the latitude effect of the soft component is 0!

in fact, denoting by indices h and s the quantities referring to the hard and the soft components, respectively,

$$l = \frac{I_{50} - I_0}{I_{50}} = \frac{I^h_{50} - I^h_0}{I^h_{50}} \frac{I^h_{50}}{I_{50}} + \frac{I^s_{50} - I^s_0}{I^s_{50}} \frac{I^s_{50}}{I_{50}} = 0{\cdot}77\, l^h + 0{\cdot}23\, l^s. \qquad (2)$$

Thus, due to the large statistical errors we cannot obtain l^s by such a difference method, but have to measure l^s directly by means of the shower intensities as in the experiments mentioned above ([4] p. 5).

As a result, we conclude with JOHNSON (1938) that

most if not all of the latitude effect at sea level, amounting to 10-20 %, *is due to the hard component.*

This conclusion is also supported by the experiments of JESSE and GILL[1] showing a latitude effect of about 30 % at sea level for large bursts (containing more than 280 particles) in ionization chambers shielded by 12 cm Pb, the effect thus being due to the hard component. The figure 30 % is, however, surprisingly high, but, as the authors point out themselves, it may not be quite certain due to the large statistical uncertainties of the experimental data.

The latitude effect of the total and the soft radiation at high altitudes has been investigated by several authors, but only little material seems to be available concerning the hard component. From the balloon flights with ionization chambers of BOWEN, MILLIKAN and NEHER[2] at the geomagnetic latitudes 60° N, 51° N, 38° N, and 3° N it follows that the *total* radiation shows a very considerable latitude effect between 60° N and 3° N at great altitude, amounting to the following values

m H_2O	6	1	0·5
$l \sim$	23 %	70 %	76 %.

For the soft component (showers in 3 G-M-counters in triangular position, covered with 1·2 cm Pb) JOHNSON[3] finds a

[1] JESSE and GILL (1939).
[2] BOWEN, MILLIKAN and NEHER (1938).
[3] JOHNSON (1935 a).

latitude effect of 24 % between 50° N and 28° N geomagnetic latitude at an altitude of 4300 m ~ 46 cm Hg ~ 6 m H_2O. Since experiments with ionization chambers measure the radiation from all directions and therefore give somewhat smaller latitude effects, JOHNSON's figure agrees very well with BOWEN, MILLIKAN and NEHER's value of 23 % between 60° N and 3° N given above; for at this altitude the soft intensity amounts already to about $\frac{2}{3}$ of the total intensity. Although a systematic investigation of the latitude effect of the soft component as a function of the altitude is still lacking, we think it may be concluded that

the latitude effect of the soft component increases highly with increasing altitude.

Regarding the latitude effect of the hard component at great altitudes we have found one experiment only, viz. that of JESSE, WOLLAN and SCHEIN,[1] giving the vertical intensity of 4 G-M-counters with 8 and 10 cm Pb absorbers in between. At an altitude of 3 cm Hg = 0·4 m H_2O they find a latitude effect of 15 % between the geomagnetic latitudes 51° N and 40° N. Consequently, the total latitude effect of the hard component, viz. between 50° and 0°, is much larger than 15 %, and *it would be interesting to obtain experimental determinations of it.* At any rate we conclude that

the latitude effect of the hard component increases with increasing altitudes, although it does not seem to assume such high values as the latitude effect of the soft component.

(III) *East-west asymmetry.*

The second important geomagnetic effect is the east-west asymmetry effect defined as

$$a = \frac{I_{west} - I_{east}}{\frac{1}{2}(I_{west} + I_{east})}, \tag{3}$$

in which I_{west} and I_{east} are the intensities from a western and an eastern zenith angle z, respectively. This asymmetry depends

[1] JESSE, WOLLAN and SCHEIN (1941).

on z, the geomagnetic latitude λ and the altitude. As the latitude effect, it may be measured for the total radiation (by means of G-M-counter telescopes), for the soft component alone (by means of 3 or more G-M-counters placed in triangular position with small bases and covered with 1-2 cm Pb, thus measuring the intensity of showers,[1] or for the hard component alone (G-M-counters placed in line with about 10 cm Pb absorber in between). Also here it is, of course, the two separate effects which are of greatest interest. At sea level the east-west asymmetry for the total radiation has been investigated by JOHNSON, ROSSI and others.[2] It is found that the effect increases with increasing values of z and decreasing values of λ, amounting at most to about $+15\,\%$ at $z = 45°$ and $\lambda = 0°$. (At $z = 30°$ and $\lambda = 0°$ it is about $+10\,\%$). This variation with z follows from the corresponding variation of the difference between the minimum energies for the western and the eastern direction.[3]

For the soft component, i. e. the showers, JOHNSON[4] finds at sea level for $z = 30°$ $a \sim +5\,\%$ in Peru, i.e. at $\lambda = 0°$. Just as was the case for the latitude effect at sea level, we may thus conclude that

the east-west asymmetry at sea level is much smaller for the soft component than for the total radiation.

For the east-west asymmetry of the hard component at sea level we have been unable to find any suitable experiments.

The variation of the east-west asymmetry with increasing altitude has been investigated by several authors. For the total radiation JOHNSON[2] finds (by means of G-M-counters in line) at $\lambda = 0°$ the following values of a

cm Hg	76	52	46
$z = 30°$ $a \sim$	$+10\,\%$	$+12\,\%$	$+13\,\%$
$z = 45°$ $a \sim$	$+15\,\%$	$+14\,\%$	$+14\,\%$.

[1] Cf. the objections to this procedure mentioned p. 6. Also the asymmetry effect for the soft component must, at any rate at sea level, be determined directly and not by a difference method, cf. p. 6.

[2] JOHNSON (1935 b), (1938). In these papers all the literature in question is quoted.

[3] LEMAÎTRE and VALLARTA (1936); also quoted in HEISENBERG (1943), fig. 9 p. 162.

[4] JOHNSON (1934).

At an altitude of 3 cm Hg, JOHNSON and BARRY[1] at the geomagnetic latitude 20° N find that for $z = 60°$ $a \sim +7\,\%$ for the total radiation as compared with $a \sim +4\,\%$ for $\lambda = 20°$ N, $z = 60°$ and at sea level ([2] p. 9).

For the soft component JOHNSON,[2] by means of 3 G-M-counters in triangular arrangement covered with 1·2 cm Pb (i. e. showers), finds that

$a \sim +1{\cdot}2\,\%\ (\pm 1\,\%)$ $z = 35°$ $\lambda = 29°$ N 4300 m above sea level $\sim$ 46 cm
$a \sim +1{\cdot}8\,\%\ (\pm 1\,\%)$ $z = 49°$ — — —

(With the same counters placed in line, but without Pb, i. e. total radiation, he finds at the same place $a \sim +10\,\%$ for $z = 35°$ and $a \sim +13\,\%$ for $z = 49°$.) We note that these figures cannot be compared with the corresponding value $a \sim +5\,\%$ mentioned above for the same experimental arrangement at sea level, because that figure referred to the geomagnetic equator, whereas the figures given here refer to $\lambda = 29°$ N. Somewhat larger values are, however, obtained for the total radiation at sea level at the same geomagnetic latitude 29° N, viz. $a \sim +5\,\%$ for $z = 30°$ and $a \sim +3\,\%$ for $z = 45°$ ([2] p. 9).

For the east-west asymmetry of the hard component, measured by means of G-M-counters placed in line with 8·6 cm Pb absorber in between, JOHNSON ([2] p. 9) finds

$a \sim +8\,\%$ $z = 30°$ $\lambda = 29°$ N 46·2 cm Hg
$a \sim +9\,\%$ $z = 45°$ — — .

These values are of the same order of magnitude as those found for the same λ, z and altitude for the total radiation, and somewhat larger than the corresponding values for the same λ and z at sea level, viz. $a \sim +3\text{-}5\,\%$ ([2] p. 9).

Finally, SCHEIN and collaborators[3] report having found a "very high positive value" for the east-west asymmetry of the hard component at the top of the atmosphere.

If we try to summarize, we see that the experimental data are rather incomplete. *What is still needed is a more syste-*

[1] JOHNSON and BARRY (1939).
[2] JOHNSON (1935 a).
[3] Private letter to prof. HEISENBERG, quoted in HEISENBERG (1943) p. 46.

matic investigation of the east-west asymmetry of the soft and the hard component separately, as a function of each of the three quantities geomagnetic latitude, zenith angle, and altitude. We think, however, that it may be concluded from the experimental data available at present that,

in contrast to the latitude effect, the east-west asymmetry of the total radiation is practically constant or rather decreasing with increasing altitude.

Remembering that most of the radiation found at sea level belongs to the hard component and that the showers show little asymmetry at sea level, we next conclude that

just as was the case for the latitude effect, most if not all of the east-west asymmetry at sea level is due to the hard component.

We may here mention that JOHNSON[1] concludes that the east-west asymmetry is a property of the hard component, also in the lower part of the atmosphere, viz. up to about 46 cm Hg, from the fact that it shows approximately a mass-equivalent absorption (when increasing Pb absorbers are interposed between the counters), whereas the soft component shows a Z^2 absorption. The latter statement, although often encountered in literature, is nevertheless false, *the soft component, both experimentally and theoretically, showing an absorption which is also approximately mass-proportional*; for the intensity is not only determined by the shower unit, given essentially by Z^2, but also by the critical energy, which is inversely proportional to Z (being defined as that energy at which the electrons lose just as much energy by bremsstrahlung as by ionization).[2] As a consequence we can only say that the experimental fact just mentioned *agrees* with the hypothesis that the asymmetry in the lower part of the atmosphere belongs to the hard component, but it does not *exclude* the other possibility that part of it belongs to the soft component, too. We think, however, that this last possibility is excluded by another experimental fact stated above, namely that the east-west asymmetry *increases* with increasing zenith

[1] JOHNSON (1938) p. 228.
[2] HEITLER (1937), ARLEY (1938).

angle. Two factors here pull in opposite directions, the increasing difference between the minimum energies ([3] p. 9) trying to increase the effect, the increasing absorption due to the increased length of the inclined paths traversed trying to decrease the effect. Now, the absorption plays only a small part for the hard component, but a dominating one for the soft component (cf. p. 21). For this component the east-west asymmetry must, therefore, be expected to be practically constant or rather decreasing with increasing values of zenith angle (except, of course, for the very smallest values for which the asymmetry equals zero) in contrast to the increase found experimentally for the total radiation and in agreement with the experimental findings for the soft component, as stated above (p. 9-10).

(IV) *Variation of the intensity with altitude.*

The investigation of the geomagnetic effects is closely connected with that of the variation of the intensity with increasing altitude above sea level. Such experiments were already carried out by Hess in order to prove that the radiation really comes from outside the earth and is not simply due to radioactive contaminations in the earth itself or its atmosphere. Later experiments, especially those by Millikan and his collaborators ([2] p. 7), showed that at the highest altitudes the intensity passes through a maximum and then decreases strongly with increasing altitude. These experiments, which were performed with ionization chambers, however give the intensity of the total radiation and from all directions, and counters are thus to be preferred, giving only the vertical intensity, although results obtained in this way exhibit larger statistical fluctuations than those obtained with chambers. The latest counter measurements for the total radiation are those performed by Pfotzer[1] at Stuttgart, i. e. geomagnetic latitude 50°N. They may thus be directly compared with the corresponding counter measurements for the hard component of Schein, Jesse and Wollan[2] (5 counter systems in line with from 4 to 18 cm Pb absorbers in between). Pfotzer's results show that

[1] Pfotzer (1936); also quoted in Heisenberg (1943) fig. 2 p. 41.
[2] Schein, Jesse and Wollan (1941 a); also quoted ibid.

to be vector-mesons, i. e. having spin 1, because the long-living mesons found at sea level must be assumed to be pseudoscalar mesons, i. e. having spin 0. The latter conclusion follows from the discussion of CHRISTY and KUSAKA,[1] who compared the predictions of the meson theory with the sea level observations of SCHEIN and GILL[2] on burst frequency versus burst energy. The comparison shows that at present the most plausible hypothesis is that the large bursts are due mainly to cascade showers produced by the bremsstrahlung emitted by the passage of pseudoscalar mesons, i. e. mesons of spin 0, through the 11 cm Pb absorber placed above the ionization chamber of SCHEIN and GILL. We must, however, object to this conclusion that it is based essentially on the application of the FURRY formula for the fluctuation of the number of electrons in a shower about the mean number. As has been shown by the author,[3] the fluctuation is, however, of varying size and as a rule much greater than that given by the FURRY formula, and these effects will presumably just be of special importance in the large showers met with in bursts.[4]

Apart from the cascade showers of the soft component also 'hard' showers have been found in which several penetrating particles are emitted in a single process.[5] These showers have been observed on Wilson chamber photographs,[6] by G-M-counters,[7] and as the photographic BLAU-WAMBACHER stars.[8] All three effects become much more frequent at high altitudes, the frequency being roughly proportional to the intensity of the soft component. We must therefore conclude that

all these effects are, directly or indirectly, produced by the photons of the soft component

(or perhaps by its electrons, but at present no processes of electrons producing either mesons or protons are known theoretically).

[1] CHRISTY and KUSAKA (1941).
[2] SCHEIN and GILL (1939).
[3] ARLEY (1943).
[4] We intend to investigate this point more closely.
[5] Cf. e. g. the review in HEISENBERG (1943), chaps. 5, 12 and 13.
[6] FUSSELL (1936) and others.
[7] JÁNOSSY and INGLEBY (1940), (1941), and others.
[8] BLAU and WAMBACHER (1937), STETTER and WAMBACHER (1939).

stead of balloons. The highest altitude attained therefore is much smaller, viz. 23 cm Hg. SCHEIN and col. find that at most 5% of the total number of mesons present at this altitude can be produced in this way. Furthermore, they show that these neutral particles cannot be neutrons and, as photons are excluded because of the upper 6 cm Pb,[1] they conclude that the particles are neutral mesons.[2] An important feature also revealed in these experiments is that about 33% of all the mesons at this altitude have energies below 5×10^8 e.v., while at sea level only a very small fraction of the mesons have energies within this range. The same conclusion follows from Wilson chamber photographs obtained by HERZOG and BOSTICK[3] in an airplane at the same altitude. These photographs furthermore indicate that the slow mesons are doubtless produced in multiple processes probably occurring in the neighbourhood of the chamber.

(V) *Various other experiments of importance for our problems.*

Finally, we shall state the results of various other experiments bearing upon our problems.

From several experiments it follows that the mesons are unstable with a mean lifetime of the order of magnitude 10^{-6} sec (mesons at rest).[4] From the YUKAWA theory of β-decay values are, however, deduced which are 10-100 times smaller. Hence we must assume two different kinds of mesons having different lifetimes (and spins).[5] It is therefore of great interest that JUILFS[6] has been able to give arguments for concluding from the variation of the intensity of the hard component with zenith angle that at high altitudes mesons may exist which have much smaller lifetimes. These short-living mesons must be assumed

[1] This, however, may not be true, since also here the photons may pass outside the upper 6 cm Pb and then produce one or several mesons giving coincidence in the 4 lower counters, as also remarked by HEISENBERG (1943) p. 51. Furthermore, a meson may be slightly scattered in the Pb above counter 2 so as to give coincidence between counters 2-5, but not in 1.

[2] Cf. also ROSSI and REGENER (1940), who give experimental evidence of the same conclusion, and ARLEY and HEITLER (1938), who draw the same conclusion from the experiment of MAASS (1936).

[3] HERZOG and BOSTICK (1941).

[4] Cf. e. g. the review in HEISENBERG (1943) p. 78 ff.

[5] ROZENTAL (1941).

[6] JUILFS (1942).

applies to the counts of the side counters measuring the showers. Finally, we should like to know whether the side counters marked 6, measuring the showers, are placed so as to measure showers with small or only those with large angle spread. In the latter case, the negative result *may* be due to the fact that the very energetic showers are very narrow, so that perhaps they may pass more or less undetected *between* the side counters without activating them. We hope that the proposed controls of this extremely important experiment will be carried out in a near future. It would also be interesting to know the intensity of photons at the top of the atmosphere, which may be measured by an anticoincidence method.

Previous to the investigation just mentioned, Schein, Jesse and Wollan[1] have carried out another experiment in order to find out whether mesons may also be created by a non-ionizing radiation. For this purpose they measured the difference between the number of coincidences 1-2-3 and 2-3-4, the counters 1 to 4 being placed in line with in all 8 cm Pb between both groups of counters. They interpreted this difference as being due to mesons produced in 2 cm Pb placed between counters 1 and 2 by a radiation which did not produce coincidences in counter 1, i.e. a non-ionizing radiation. They found that up to 6·6 cm Hg this difference increased roughly proportionally to the intensity of the total radiation, i.e. practically proportionally to the soft radiation, which indicates that the non-ionizing radiation in question was the photons of the soft component. This conclusion, however, is not quite unambiguous as the difference may also be partly due to mesons passing outside of the counter 1 and being very slightly scattered in the 2 cm Pb between counters 1 and 2.[2]

The same objection applies to the experiment of Schein, Wollan and Groetzinger.[3] They use an experimental arrangement similar to that of Schein, Jesse and Wollan,[1] except that now 6 cm Pb is placed above all the counters to exclude photons, and that the experiments are performed in an airplane in-

[1] Schein, Jesse and Wollan (1939), (1940).

[2] If the diagram of the experimental arrangement given in the paper is in true scale, it is even possible to draw a *straight* line through counters 2, 3 and 4 which does not pass through counter 1!

[3] Schein, Wollan and Groetzinger (1940).

the intensity of the total radiation increases steadily up to a maximum at about 8 cm Hg,

at which altitude the intensity is approximately 50 times that at sea level, and then falls off rapidly at higher altitudes. Next, SCHEIN, JESSE and WOLLAN's results show, firstly, that

the hard component does not pass through any maximum, but increases up to the very greatest heights attained,

viz. 2 cm Hg. Secondly, that

all the points for the 4, 6, 8, 10, 12, and 18 cm Pb absorbers lie on the same curve.

In the experiments of SCHEIN, JESSE and WOLLAN, two side counters were, furthermore, operating in order to detect also showers (containing at least 2 particles) produced in 4 and in 6 cm Pb. The result was negative, in that

only a few per cent of the particles traversing 4 and 6 cm Pb were accompanied by showers.

This important experiment is interpreted by the authors as proving that at the top of the atmosphere practically no electrons with energies able to penetrate the 4 cm Pb, i. e. 10^9-10^{12} e.v., can be present, because (a) the penetrating power of the particles measured is constant, (b) they are non-shower-producing. Since the magnetic field of the earth at 56°N cuts off all electrons below 3×10^9 e. v., and since the measurements were carried out up to 2 cm Hg, which is within one shower unit (= 2·6 cm Hg), they furthermore conclude that

in the energy region 10^9-10^{12} e.v. the primary cosmic radiation can contain only a few per cent primary electrons.

As SCHEIN, JESSE and WOLLAN point out themselves, it is, however, necessary to perform control experiments with 2, 1, and 0 cm Pb between the counters in order to obtain the transition to the PFOTZER curve mentioned above. Moreover, it should be emphasized that the thicknesses which are of most interest in this connection, viz. 4 and 6 cm Pb, are represented by only one point each at about 3 cm Hg, but not in the other parts of the curve, especially not at the maximum of the PFOTZER curve. The same

As to the nature of these hard showers it is experimentally found that the showers observed on Wilson photographs consist mainly of mesons together with a few protons. The same is probably true for the hard showers measured by JÁNOSSY and INGLEBY, whereas the photographi stars are known to consist of protons and neutrons (together perhaps with a few mesons). The single protons and neutrons also found in cosmic radiation (cf. p. 5) can probably be fully accounted for as resulting from the explosions observed as the stars.[1] We must thus at present conclude that

there are two different types of non-cascade showers, the explosion showers and the evaporation showers.

The explosion showers consist of mesons produced by multiple processes in which presumably a primary, very energetic photon is absorbed. The protons which may accompany these processes arise from a transfer of a certain part of the energy to the nuclei at which the mesons are produced, thus giving rise to a more or less local heating up and a subsequent evaporation of nucleons. The energies of both the incident particle and the mesons produced as a rule being relativistic in these processes, we must expect the angular dispersion to be rather small, but we are unable to judge whether this agrees with experiments or not. In the evaporation showers the processes are presumably the same, except that the primary photons are less energetic than in the explosion showers so that the binding of the nucleons plays a more dominant rôle. Consequently, most of the energy is transferred to the nucleus in the form of greater heating up. As a result, most of the particles emitted are protons and neutrons and only a few particles are mesons. Both the primary particle and the evaporation particles produced having non-relativistic energies, we must in this case expect a more uniform distribution in space of the particles emitted, as is just found experimentally in the BLAU-WAMBACHER stars.

So far as we can judge, only Wilson chamber photographs have been found showing the direct creation of mesons or protons from primary photons, but not from primary mesons, protons, or electrons. Theoretically, the evaporation showers

[1] Cf. the discussion in HEISENBERG (1943) p. 124 ff.

may also be produced by primary protons and neutrons by 'nuclear ionization',[1] in which the incident particle gives off part of its energy by inelastic collisions, thereby heating up the nucleus, which then evaporates. This process, however, does not seem to have been directly observed. Also such showers may theoretically be produced by the absorption of slow negative mesons[2] (the slow positive mesons being repulsed by the Coulomb forces); for this process will take place long before the radioactive decay. Although this effect seems indirectly verified by the fact that at sea level more positive mesons are found than negative mesons, and next by the experiment of RASETTI[3] who finds that roughly only half of all mesons decay radioactively, the rest being absorbed without decay, no direct evidence seems to have been found, i. e. a Wilson photograph showing a slow meson being absorbed under the emission of several protons.

Finally, the extended showers found by AUGER and collaborators[4] should be mentioned. They measured coincidences between G-M-counters placed up to several 100 meters apart. It has been discussed whether these AUGER showers consist of electrons or of mesons. From absorption measurements AUGER and KOLHÖRSTER assumed them to consist mainly of electrons together with a few mesons, because the number of coincidences was only reduced to about 25 % behind 15 cm Pb. At any rate, from Wilson chamber photographs it follows that most of the particles are very energetic electrons.[5] Assuming the AUGER showers to be cascade showers formed at the top of the atmosphere and reaching their maximum at about sea level, it follows that such cascades are not absorbed even in 15 cm Pb. As shown by MOLIÈRE,[6] the cascade theory can actually account for *all* the particles being electrons. Such showers representing at sea level energies up to 10^{15} e. v., they must have been produced by primary particles of energies even up to 10^{18} e. v.

[1] HEISENBERG (1937).
[2] TOMONAGA and ARAKI (1940).
[3] RASETTI (1941).
[4] AUGER and col. (1938), KOLHÖRSTER and col. (1938).
[5] JÁNOSSY and LOVELL (1938), AUGER and col. (1939).
[6] HEISENBERG (1943) p. 35 ff.

Part 2. The various possible hypotheses regarding the primary component.

Having reviewed the main experimental facts of importance for our fundamental problems, (b) and (c) p. 3, we now turn to the next question: by what hypotheses regarding the primary component can we correlate and explain this vast experimental material? We have the following possibilities regarding the primary constituents:

photons, electrons, neutrons, protons, mesons, and neutrinos,

together with combinations of all these particles.

First of all we can exclude the neutrons and the charged mesons, as these particles are unstable with mean lifetimes of the order of magnitude one hour and 10^{-6} sec, respectively. The latter result is deduced experimentally, the former theoretically, but without being verified experimentally. This verification is presumably also impossible because the neutrons are slowed down and absorbed by the various nuclei even in the atmosphere long before they would have time to decay.[1] Furthermore, we shall at once exclude the hypothetical neutrinos from our considerations, as their existence has not yet been directly demonstrated (cf. however the remark on p. 4).

From the geomagnetic effects it follows that at any rate a certain fraction of the primary particles are charged particles. (We note that these effects obviously operate *outside* the atmosphere, the thickness of which is only of the order of magnitude $\frac{1}{10}$-$\frac{1}{100}$ of the radius of the earth). From the very high values, viz. 70-80 %, for the latitude effect of the total radiation at great altitudes, i.e. practically the soft component, it follows that most of the primary particles of the soft component must be charged particles. Millikan and col.[2] estimate that

the energy brought into the atmosphere by non-charged particles can at most amount to 20 % of that brought by charged particles.

To obtain as simple a description as possible we shall, therefore, also exclude photons and neutral mesons as primary particles of the soft component. Of course, Nature need not at

[1] Heisenberg (1943) p. 141.
[2] Bowen, Millikan and Neher (1938).

all be simple, and in fact cosmic rays have proved to be far more complicated than anybody has at first imagined. Nevertheless it is generally agreed that to begin with we should try the simplest hypotheses before having recourse to the more complicated ones.

For the hard component the latitude effect as a function of altitude, as mentioned above p. 8, has not yet been fully investigated. Thus, we cannot at present exclude the possibility that a more considerable fraction of the hard component is due to non-ionizing primary particles than the soft one. We shall, however, also here, for the sake of simplicity, assume that *the whole* of the hard component is due to primary charged particles. Consequently in both cases only electrons alone, protons alone, or a combination of these particles remain.

(I) *The electron hypothesis.*

According to this hypothesis[1] the soft component mainly consists of cascade showers from the primary electrons, the integral energy spectrum of which must be assumed to be of the form

$$F(E) = \text{const } E^{-\gamma} \qquad \text{for } E > 1\text{-}2 \times 10^{9} \text{ e. v.}, \qquad (4)$$

in which we must insert $\gamma \sim 1{\cdot}8$ in order to fit the experiments.[1] Next, the hard component is assumed to consist of secondary mesons produced by the photons of the soft component. Hence the intensity of the hard component must pass through a maximum and approach zero at the top of the atmosphere. As regards the proportion between positons and negatons, JOHNSON[2] has concluded from the very small east-west asymmetry of the soft component at sea level and at 4300 m altitude that there must be practically the same number of positons and negatons (cf. p. 10). This conclusion does not, however, follow unambiguously from the experiments mentioned. From the cascade theory it follows, firstly, that at sea level a soft component produced as cascade showers from either photons, positons, or negatons can show a latitude effect of at most a few per cent and the

[1] This hypothesis forms the basis of the surveys of EULER and HEISENBERG (1938), HEITLER (1938), and ARLEY (1940).

[2] JOHNSON (1935 a).

same, therefore, applies to the east-west asymmetry.[1] At 4300 m altitude, HEITLER[1] estimates the latitude effect at 17 %. The corresponding east-west asymmetry has not been worked out, but as a zenith angle z at this altitude increases the layer of air traversed by the shower from $l = 17$ to $l = \frac{17}{\cos z} \sim 20$ and 24 (l measured in shower units) for $z = 30°$ and $z = 45°$, respectively, the primary energies necessary to penetrate this distance will certainly be such as to reduce the east-west asymmetry to at most a few per cent (cf. the discussion on p. 12). *Consequently, we can draw no conclusions as to the sign of the primaries of the soft component from its east-west asymmetry in the lower part of the atmosphere.*

From the east-west asymmetry of the hard component it follows, on the other hand, due to its small absorption (the mesons only losing about 2×10^9 e.v. during their passage through the whole atmosphere) that its primaries must consist of more positive than negative particles. If SCHEIN's experiment mentioned above ([3] p. 10) turns out to be reliable, we must even conclude that

all the primary particles of the hard component are positively charged,

as first concluded by JOHNSON.[2]

Thus we must assume either that the primary radiation mainly consists of positons, or that the mesons can only be produced by the primary positons, but not by the primary negatons. The latter possibility must be rejected at once, because the showers produced by primary electrons of either sign are after some distance practically identical in the number of photons, positons, and negatons, respectively, and it is impossible to imagine processes by which the mesons of the hard component should be produced only by the primary, but not by the secondary electrons. Furthermore, we must at present assume that the mesons are produced only by the photons and not directly by the electrons of the soft component.

We are thus forced to assume the primary electrons to be

[1] HEITLER (1937), ARLEY and ERIKSEN (1940).
[2] JOHNSON (1938), (1939a), (1939c). Cf. also ALFVÉN (1939b).

mainly positive. But this conclusion involves some difficulties. Firstly, both the soft, the hard and thus the total radiation should in this case show a very large positive east-west asymmetry at great altitudes in contrast to the above discussed experiment of JOHNSON and BARRY ([1] p. 10) finding only $a \sim +7\,\%$ for the total radiation against an expected value $\sim +60\,\%$ on the hypothesis that the primary radiation consists only of positive particles. *We think this experiment is already a crucial one, which alone is enough to reject the electron hypothesis.* It has, however, been objected to this conclusion that the negative result of the experiment may also be explained by assuming that the direction of the primary particles is not conserved, but is quite blurred by the processes producing the secondary particles.[1] Against this argument it must first of all be pointed out that it seems difficult to understand why this effect should be more pronounced in the upper than in the lower atmosphere or at sea level, where the total radiation shows a considerable east-west asymmetry. If the particles are cascade electrons, most of them will have energies about or rather above the critical energy of air, viz. $1{\cdot}5 \times 10^8$ e.v., which is much higher than the rest energy of the electrons, and both from the cascade theory of showers and directly from Wilson chamber photographs it then follows that the angular dispersion is very small. Next, by whatever processes particles are created from primary particles of relativistic energies, it follows simply from the Lorentz transformation from the center of gravity coordinate system to that in which the process is observed, that all the particles emitted have very nearly the same direction as the primary particle.[2]

We cannot either agree with the conclusion drawn by JOHNSON[2] from the experiment of JOHNSON and BARRY just discussed, that the primary particles of the soft component are equally positively and negatively charged. We must remember that at the altitude at which this experiment is carried out, viz. 3 cm Hg, the total radiation consists of about $57\,\%$ mesons and only $43\,\%$ electrons (as judged from the curves of PFOTZER and of SCHEIN,

[1] HEISENBERG (1943) p. 45.
[2] Cf. also JOHNSON (1939 a), (1939 b), who reaches the same conclusion from other arguments.

JESSE and WOLLAN[1]); together with SCHEIN's result mentioned above ([3] p. 10) that the east-west asymmetry of the hard component is very considerable, we can thus only conclude from JOHNSON and BARRY's experiment showing a very small east-west asymmetry of the total radiation at great altitude, that *the soft component shows a negative east-west asymmetry at great altitude. This result should, of course, be verified directly.*

A second difficulty in assuming the primary radiation to consist of considerably more positive than negative particles is that it becomes difficult to understand the propagation of the radiation in interstellar space. As pointed out by SWANN,[2] any difference in the space charge of positive and negative particles of any kind would give rise to potential differences quite irreconcilable with the further passage of charged particles through space. (Furthermore ALFVÉN[3] has pointed out that such a difference would also give rise to large magnetic fields. The effect of these fields seems, however, only to be that they make the radiation *isotropic*). Consequently, it is necessary that *in distances far away from the sources of the radiation it must consist of the same number of positive and negative particles.*

Thirdly, the SCHEIN-JESSE-WOLLAN experiment ([2] p. 12) is probably the most crucial experiment which makes the electron hypothesis irreconcilable with experimental facts, quite apart from what detailed picture we may accept of the genesis of the various components. If this experiment is reliable (in spite of the minor objections which, as we have pointed out, may be raised against it (p. 13)), it means partly that the hard component does not pass through any maximum but increases steadily, partly that the primary radiation can at most contain a few per cent electrons, both facts strongly disagreeing with the electron hypothesis.

(II) *The proton hypothesis.*

According to this hypothesis both the soft and the hard component are secondary radiations produced by protons having the same integral energy spectrum (4) as the electrons had previously.

[1] Fig. 1 in SCHEIN, JESSE and WOLLAN (1941), reproduced as fig. 2 in HEISENBERG (1943) p. 41.

[2] SWANN (1933). Cf. also JOHNSON (1939 a).

[3] ALFVÉN (1938), (1939 a).

The intensity of the soft component must, therefore, approach zero at the top of the atmosphere, whereas the hard component must increase steadily since very energetic protons also behave like penetrating particles. As just discussed it is, however, on this hypothesis quite impossible to understand the small east-west asymmetry of the total radiation at great altitude. Next, as also just discussed, it makes the propagation of the radiation in interstellar space impossible. Finally, it makes it quite impossible to understand the latitude effect of the soft component amounting to 70-80 % at great altitude; for the electrons could only be produced by processes in which they obtain only a fraction of the primary energy. This primary energy must, therefore, be much higher than if the primary particles were electrons. But when the main contribution to the intensity of the soft component comes from the higher part of the energy spectrum (4), the variation of the minimum energy with geomagnetic latitude will be of little importance. Consequently, the latitude effect becomes much smaller, at most a few per cent, as also emphasized by HEISENBERG.[1] That the secondary electrons can in fact obtain only a fraction of the primary energy is clearly seen by considering those processes by which protons could produce soft showers: by knock-on electrons, by bremsstrahlung and through intermediate mesons. In the latter case, it might be suggested that the soft component in the upper atmosphere is mainly due to the radioactive decay of the very short-living vector-mesons with spin 1, the hard component consisting of the longer living pseudoscalar mesons with spin 0 (cf. p. 15). Now it follows both theoretically[2] and experimentally[3] that the mesons are mainly produced in multiple processes, each meson thus obtaining on the average only a fraction of the primary energy. Furthermore, on an average half the energy of each meson is carried away by the neutrinos. As a result most of the shower intensity would be produced by primary protons with energies beyond the field sensitive region, viz. about $2\text{-}15 \times 10^9$ e.v., and the soft component could show practically no latitude effect even at very high altitudes.

[1] HEISENBERG (1943) p. 5.
[2] Cf. e. g. HEISENBERG (1943), SWANN (1941), and others.
[3] Cf. e. g. SCHEIN, JESSE and WOLLAN (1941b).

The proton hypothesis must, consequently, also be regarded as irreconcilable with the experimental facts.

(III) *The combined electron-proton hypothesis.*

According to this hypothesis[1] the soft component in the upper atmosphere is produced as cascade showers from primary electrons, whereas the hard component is mainly produced from primary protons. From the above discussion of the very small east-west asymmetry of the total radiation together with Swann's neutrality argument regarding the number of positive and negative particles in the radiation in interstellar space, it follows that the primary *electron* component must consist practically of only *negatons* in a number equivalent to that of the protons. The only crucial experiment which forces us to reject this in all other respects excellent hypothesis is thus the experiment of Schein, Jesse and Wollan ([2] p. 12), which shows that there can only be at most a few per cent electrons present at the top of the atmosphere.

Summarizing our discussion, we must thus conclude that *the total present experimental evidence is irreconcilable with any of the hypotheses theoretically possible using the particles known at present.* For this negative result the crucial experiments are those of Johnson and Barry ([1] p. 10), Schein, Jesse and Wollan ([2] p. 12), and the latitude effect of the soft component at great altitude. Also the neutrality argument of Swann ([2] p. 23), necessary for the propagation of a charged radiation in interstellar space, leads to the same conclusion. We may thus say that

there is at present indirect experimental evidence for the existence of a new and hitherto unknown particle in the primary cosmic radiation,

and we think that the most plausible hypothesis which may be set up as to the nature of this new particle is to assume it to be a *negative proton.*

[1] This hypothesis has been favoured by Johnson (1938), (1939 a).

Part 3. The hypothesis of the existence of negative protons in the primary cosmic radiation.

As mentioned in the introduction, this hypothesis has been put forward by the author from the arguments discussed above, and by Klein from arguments regarding the origin of cosmic rays.[1] In this part, the consequences of this hypothesis, and in the last part Klein's theory will be discussed.

We assume on this hypothesis that

the primary cosmic radiation consists of positive and negative protons with the integral energy spectrum given in (4), *p.* 20,

previously assumed to belong to electrons. From Swann's neutrality argument we assume that

the numbers of positive and negative protons are practically equal.

Next, we assume that most negative protons will be absorbed by the positive protons at the top of the atmosphere or in the very upper part of it, their total kinetic plus rest energy thereby being transformed into 2 annihilation photons which, due to the conservation of energy and momentum, obtain the same energy and equal, but opposite momenta, uniformly distributed in space in the center of gravity coordinate system. (A *one*-quantum annihilation process is impossible for free protons, and less probable for bound protons than the *two*-quantum process). Due to the Lorentz transformation they will then, as discussed above on p. 22, in the coordinate system in which we observe the process, have practically the same direction as the incident negative proton and energies practically uniformly distributed up to $2Mc^2$ + kinetic energy of the negative proton. These photons then immediately give birth to cascade showers which at higher altitudes constitute most of the soft component. The most energetic of these showers constitute the large Auger showers, which extend even down to sea level, together with some of the large bursts. Some of the photons may also be absorbed under the emission of mesons, especially more slow mesons.[2]

[1] Arley (1944), Klein (1945).

[2] This last process seems, however, to occur very seldom as compared with the absorption of photons leading to pair production. This is shown by the fact that the cascade theoretical Rossi curves fit the experimental curves of

These slow mesons may then be absorbed, if they are negatively charged (cf. p. 18), giving rise to nuclear evaporation processes in the form of BLAU-WAMBACHER stars, most of which, however, are probably produced directly by the absorption of photons.

As the kinetic energy of the incident negative proton is large as compared with the binding energy of the positive protons and the neutrons in the nuclei they meet in the atmosphere, we may neglect this binding and regard the nucleons as being free. By these annihilation processes we therefore assume that no or little heating up of the rest of the nuclei takes place, and therefore presumably few evaporation nucleons will be emitted. The single protons and neutrons found experimentally we assume to be the result of the stars (cf. the discussion on p. 17).

It may also be possible that some of the negative protons are annihilated in other processes by which mesons are created. In such cases, it is most probable from current theoretical ideas (cf. p. 24) that these processes are multiple, whereby several mesons are created in one elementary act. In order not to complicate the theory more than necessarily, and also because of the above discussion of the latitude effect of electrons produced from the mesons of these processes (p. 24), *we shall, however, tentatively assume that only the photon annihilation is of importance.*

Although most negative protons should on our hypothesis be annihilated in the upper part of the atmosphere, some of them might of course happen to penetrate to the lower parts of the atmosphere. *It is, therefore, possible to obtain direct experimental evidence on our hypothesis by looking for negative protons on Wilson chamber photographs from high altitudes such as mountains or airplanes.*

As for the *positive protons* of the primary radiation we set up the same hypothesis as e. g. JOHNSON in the previous proton or electron-proton hypothesis, viz. that in the upper atmosphere they are momentarily or gradually transformed into mesons (which are presumably only pseudoscalar mesons, as discussed

ROSSI and JÁNOSSY (1939), TRUMPY (1943), NERESON (1942), and others, even up to the highest thicknesses of absorbers employed in these experiments (cf. the theoretical calculation and the comparison with these experiments in ARLEY (1943) chap. 6). On the other hand, the experiments of SCHEIN and col. ([1] and [3] p. 14) seem to show that such processes do occur in the atmosphere.

below p. 29). It may also, of course, be possible that very energetic protons emit bremsstrahlung and knock-on electrons, thereby producing cascade showers which form part of the soft component, but these effects may presumably be entirely neglected. On the other hand, the hard component produces a considerable soft secondary radiation by the radioactive decay electrons of the mesons, and by the knock-on electrons and bremsstrahlung also produced by the mesons, giving at once rise to cascade showers denoted as decay and interaction showers, respectively. These showers presumably form most of the soft component found at sea level.

We shall now discuss the consequences of our hypothesis and the above mentioned assumptions and compare them with the experimental evidence given in part 1.

First, by its very construction our hypothesis is seen to agree with SWANN's neutrality argument. Secondly, the soft component is seen to pass through a maximum, approaching zero at the top of the atmosphere as was found experimentally by PFOTZER and by SCHEIN, JESSE and WOLLAN ([1] and [2] p. 12). Thirdly, the *total* energy of the negative protons is transferred to the soft component produced, and next nearly the same fraction of the negative protons as of the electrons, previously assumed to be the particles having the energy spectrum (4) p. 20, have now energies in the field-sensitive region, viz. about $2\text{-}15 \times 10^9$ e.v. for electrons; for this energy region is practically the same also for high speed protons (although somewhat lower).[1] Consequently, our hypothesis also leads to the same high values of the latitude effect of the soft component at great altitude as did the electron hypothesis, and as is found experimentally. That part of this soft component which reaches sea-level would, however, just as was the case in the electron hypothesis, now be produced mostly by protons in the non-field-sensitive region and would, consequently, show a latitude effect and an east-west asymmetry (although negative) of at most a few per cent at sea level. Both these effects would, on the other hand, increase very much with increasing altitude. On our hypothesis the soft component should thus at high altitude, where the

[1] Cf. e.g. JOHNSON (1938) table II p. 219, also quoted in HEISENBERG (1943) table 1 p. 152.

contribution to the soft component from the hard component is only small, show a considerable east-west asymmetry in the *opposite* direction of the hard component, i. e. a preponderance of negative primaries, or greater intensity from the east. It should, however, here be noted that this conclusion is based on the assumption that the mesons produced by the positive protons mostly are long-living pseudoscalar mesons. If also a considerable number of short-living vector mesons were produced in these processes, they would already at high altitudes decay into electrons at once giving birth to cascade showers. As a result, the east-west asymmetry of the soft component at great altitude would in this case be less negative or even practically zero. *The direct experimental determination of the east-west asymmetry of the soft component at great altitude is thus of fundamental importance*, although JOHNSON and BARRY's experiment already gives strong evidence of a considerable *negative* east-west asymmetry of the soft component at great altitude, as discussed above (p. 23). Furthermore, this east-west asymmetry of the soft component should be practically non-increasing with increasing zenith angle (cf. p. 12).

As for the hard component, it is firstly seen that on our hypothesis it does *not* pass through any maximum, but increases steadily up to the very greatest heights. As already stated, the primary protons, having relativistic energies, will behave as a hard component whether they are transformed immediately or gradually into mesons. Next, the hard component now shows the same geomagnetic effects as in the previous proton hypothesis, viz. a latitude effect at sea level of the order of magnitude 10-20 $^0/_0$, which increases with increasing altitude, but less strongly than that of the soft component, because the mesons only lose about 2×10^9 e. v. by their passage through the whole atmosphere. We think that also this statement is in agreement with the experiments although the data are here rather scanty, as discussed on p. 8. Finally, for the same reasons our hypothesis leads to a positive east-west asymmetry already at sea level. Furthermore, this positive east-west asymmetry must increase with increasing altitudes and with increasing zenith angle (cf. p. 12), which statements are both in agreement with the experimental findings.

Combining the latter result with the result of the negative east-west asymmetry of the soft component, we thus see that our hypothesis leads to an east-west asymmetry for the total radiation which decreases with increasing altitude, as is just found experimentally by JOHNSON and BARRY ([1] p. 10; cf. also the discussion on p. 22). *We think that this crucial experiment is a strong argument in favour of our hypothesis.*

We note that it might be thought possible to test experimentally, if our hypothesis is at all accepted, whether the soft component in the upper atmosphere is produced through intermediate vector mesons (cf. above p. 24). For the lifetime of these particles we must presumably assume values of the order of magnitude 10^{-8} sec. In that time, they would on an average move a distance of $10^{-8} . 3 . 10^{10} . \frac{E}{\mu c^2}$ cm $\sim$ 100 m (the velocity being relativistic, and the factor $\frac{E}{\mu c^2} \sim 40$ being the relativistic time factor). Thus, those vector mesons produced in the neighbourhood of the measuring apparatus would pass through it as a hard radiation, but as one showing a *negative* east-west effect. At that altitude at which the hypothetical transformation, negative protons to vector mesons, should take place, we thus might observe a temporary decrease in the east-west asymmetry of the hard component. We think, however, that in view of the fact that such vector mesons must be created in multiple processes, if at all created, this eventual decrease could only amount to a few per cent and thus presumably only be within the measuring errors.

At sea level most of the soft component is presumably due to the decay and interaction showers mentioned above (p. 28),[1] and it could therefore only show a latitude effect of at most a few per cent, these showers representing only a fraction of the energy of the primary particles from which they have been produced. As the same applied to the cascade showers produced from the negative protons, the total soft component at sea level should show a latitude effect of at most a few per cent, as just found experimentally.

As regards the east-west asymmetry of the soft component produced from the hard one, it could also for the same reasons

[1] In HEISENBERG (1943) p. 90, it is estimated that at sea level the soft component is composed of about 62 % decay showers (Z), 17 % interaction showers (W) and 21 % cascade showers (R) (the last originating according to our hypothesis from the negative protons).

as for the latitude effect amount to at most a few per cent, but in the *opposite* direction of the east-west asymmetry of the part of the soft component produced by the negative protons. Consequently, the east-west asymmetry of the total soft component at sea level must be practically zero, as is just found experimentally. With increasing altitude the cascade part of the soft component becomes more and more dominating, and the east-west asymmetry of the soft component should thus on our hypothesis decrease with increasing altitudes, becoming more and more negative, as is indirectly verified by the experiment of JOHNSON and BARRY (cf. the discussion on p. 22).

As for the meson showers and the nuclear stars, i. e. the explosion and the evaporation showers, respectively (cf. p. 16 ff.), it follows from our hypothesis (p. 27) that their frequency should increase roughly proportionally to the intensity of the soft component, as just found experimentally. KLEIN,[1] however, has also suggested the possibility that the stars may be due to the absorption of slowed down negative protons. As here the binding of the nucleons must come into play, such an absorption would lead to a strong heating up of the nucleus and a subsequent evaporation in contrast to the case of very fast protons (cf. p. 27). Also this process would explain that the frequency of the stars increases very strongly with increasing altitude. Although, as we have seen, it is unnecessary to have recourse to this explanation of the stars, because they are equally well explained as the result of the direct absorption of photons (or perhaps of slow negative mesons), we would not exclude the possibility of the existence of such processes.

KLEIN[1] has also suggested another explanation of the very large AUGER showers in order to account for the occurrence of the enormous energies, viz. 10^{15}-10^{18} e.v., necessary if they are to be explained as cascade showers produced at the top of the atmosphere and penetrating down through the whole of the atmosphere to sea level. KLEIN suggests as another explanation that there may also in the primary radiation exist whole grains or dust particles consisting of reversed matter, i. e. matter the atoms of which consist of negative protons, 'antineutrons' and positons (cf. the last part of the present paper). When these grains

[1] KLEIN (1945).

of reversed matter hit the atmosphere, all their constituents are annihilated successively during a very short time by a chain of annihilation processes so that a very large number of very energetic particles are produced within a very narrow space. If it is possible that the particles resulting from these annihilations are mostly photons or electrons, or are immediately transformed into such by cascade multiplication of photons or of the electrons from the radioactive decay of intermediate mesons, we think this to be a most promising explanation of the extremely high total energies revealed in the AUGER showers, these energies now resulting from many primary particles which are transformed practically simultaneously, instead of from one single parent particle as in the previous explanation. The result must, however, on whatever explanation given be electrons, as the AUGER showers are experimentally known to consist mostly, if not exclusively, of electrons (cf. the discussion on p. 18).

Summarizing, we think it may be said that *our hypothesis is able to explain, at any rate qualitatively, all the present experimental evidence.* In fact we have not found any experiment directly contradicting it, but we stress that, of course, *only further experiments can show whether our purely tentative hypothesis contains part of the truth or perhaps even the whole truth of the genesis of cosmic rays.*

Regarding the more quantitative side of the hypothesis it is, due to the very incomplete state of the present quantum theory within these high energy regions, premature to try to deduce any numerical results e.g. for the various intensities and the geomagnetic effects. As discussed by the author,[1] our hypothesis demands a cross section of the order of magnitude 10^{-25} cm^2, i. e. nuclear dimensions, for the fundamental process of the two-quantum annihilation of a negative and a positive proton. Against this, the present DIRAC equation, *which, applied to protons, just demands the existence of negative protons,* gives only a cross section of the order of magnitude 10^{-32} cm^2, i. e. smaller by a factor 10^7. Since we are in these processes far beyond the limits of validity of the

[1] ARLEY (1944).

present quantum theory, as estimated by HEISENBERG ([1] p. 32), this discrepancy may not be so serious, especially when we also keep in mind that the negative protons may certainly participate in quite different processes, the calculation of which is beyond the capacity of the present quantum theory.

Part 4. On the origin of cosmic radiation.

As mentioned in the introduction, the idea of assuming the existence of negative protons in the primary cosmic radiation has also been put forward in a paper by KLEIN.[1] The purpose of this paper, however, is not that of explaining the present experimental data on the behaviour of the radiation in the atmosphere of the earth, but to answer our question (a) p. 3, i. e. to explain the origin of the enormous energies of the cosmic rays. As already pointed out by MILLIKAN and his collaborators,[2] the average energy of the primary energy spectrum (4) p. 20, viz. about 4×10^9 e. v., is just of the same order of magnitude as the rest energy of those nuclei which, from astronomical observations, are known to occur most frequently in interstellar space, namely H, He, C, N, O, and Si. MILLIKAN and his coworkers therefore suggested that the source of the cosmic radiation is simply to be sought in nuclear processes in which these nuclei are annihilated, the rest energy being given off in the form of two electrons. (At least *two* electrons in order to obey the conservation laws for energy and momentum). Due to these conservation laws, the electrons carry each half the energy and have equal, but opposite momenta which are uniformly distributed in space. From this hypothesis we should expect the primary energy spectrum to be not continuous, as assumed in formula (4), but *discrete*, having only the energies corresponding to half the rest energies of the nuclei mentioned, viz.[3]

[1] KLEIN (1945).
[2] BOWEN, MILLIKAN and NEHER (1938).
[3] 1 atomic unit is the rest energy Mc^2 of $\frac{1}{16}$ of O^{16}, i. e. $931 \cdot 05 \times 10^6$ e. v (cf. e. g. BETHE (1936) p. 86). The atomic weight of the proton being 1·00813, the rest energy of H^1 is $0 \cdot 9386 \times 10^9$ e. v., etc.

	H^1	min. en.	He^4	C^{12}	N^{14}	O^{16}	Si^{28}	max. en.
Energy in atomic units	0·5	..	2	6	7	8	14	..
Energy in 10^9 e.v.	0·47	1·4	1·9	5·6	6·6	7·5	13·2	16·5
Corresponding geomagnetic latitude		60°N U.S.A.	56°N U.S.A.	42°N U.S.A.	40°N U.S.A.	33°N U.S.A.	20°N India	0° India

In this table we have also given the geomagnetic latitudes at which these energies represent the minimum energy (for electrons) for the direction of easiest access, which is smaller than the minimum energy for the vertical direction.[1] Since the magnetic dipole of the earth is situated excentrically, these minimum energies vary slightly with longitude.[2] For protons the minimum energies are somewhat smaller for the same latitude.[3] The column denoted by min.en. in the table gives the minimum energy found in the primary spectrum for easiest access, which is generally ascribed to the blocking effect of the sun. The column denoted as max. en. gives the largest minimum energy for vertical incidence at the equator.

On MILLIKAN's hypothesis we should thus expect the intensity of cosmic radiation in the stratosphere to have a banded structure, being constant between the geomagnetic latitudes corresponding to these energies and increasing each time such a latitude is passed from north to south. This effect MILLIKAN and collaborators[4] in fact claim to have observed. Their observations are, however, carried out with ionization chambers and the measurements, therefore, give the total effect of both the soft and the hard component and from all directions. *So it would be more adequate to use G-M-counters and thus try to ascertain whether the effect, if real, exists for the soft, the hard, or both components. Furthermore, the east-west asymmetry should then also show a banded structure*, an effect which does not yet seem to have been observed.

[1] Cf. e.g. JOHNSON (1938) fig. 14 p. 219.
[2] Cf. e.g. JOHNSON (1938) fig. 16 p. 222.
[3] Cf. e.g. JOHNSON (1938) table II p. 219.
[4] MILLIKAN, NEHER and PICKERING (1942), (1943).

However, from a theoretical point of view a process in which nuclei are annihilated, just two electrons thereby being emitted, is quite an unknown process. Furthermore it is irreconcilable with the conservation of charge, and in general also of spin and statistics, which conservation laws are just as fundamental as those for energy and momentum. In order to overcome these theoretical difficulties and yet to be in agreement with the banded structure postulated by MILLIKAN and col., KLEIN has put forward the following hypothesis.

From general theoretical considerations one would expect a perfect symmetry between the positive and negative electricity in the world, a symmetry which was much emphasized by DIRAC's electron theory and the subsequent experimental discovery of the positon. Thus, there ought also to exist what KLEIN calls reversed matter, in which all electric signs are reversed, i.e. which consists of negative protons, 'antiprotons, positons and antineutrons, the magnetic moment of which has a direction with respect to the spin momentum opposite to that of ordinary neutrons. Applying the DIRAC equation also to the nucleons, a positive and a negative proton, as well as a neutron and an antineutron, should be able to annihilate each other just as a positon and a negaton can annihilate each other under the emission of two photons (which process is more probable than the one-quantum annihilation process being possible for bound particles), whereby the photons become equal energies and equal but opposite momenta. The annihilation can perhaps also take place under the emission of two or more mesons.

Since the spectra emitted by ordinary and by reversed matter would be identical, it would be impossible to ascertain whether a given star consists of one or the other form of matter. Assuming the stars of each galactic system to have a common origin, KLEIN now also assumes that all the stars of one galactic system consist of the same kind of matter, but of matter different from one galactic system to another. In the intergalactic space nuclei of both kinds may exist together, due to the extremely small density of matter present there. KLEIN next assumes that these nuclei move about with thermal velocities and by their collisions are at once annihilated as soon as different kinds of matter come into contact with each other, thus giving birth to the cosmic rays. Now, as mentioned above, the most frequent nuclei are H, He and then C, N, O and Si, which occur in the approximate ratio 100:10:1:1:1:1.[1] Collisions between *like* nuclei will lead to total annihilation, the energy being given off either (a) as two photons, or (b) as two or more mesons. KLEIN assumes that (b) is the dominating process and that just *two* mesons are formed. These mesons will next decay, emitting an electron and a neutrino. KLEIN now argues that, as the nuclei are assumed to move with thermal velocities, each meson will get exactly the rest energy of one nucleus and the electrons therefore practically half that energy, thus just leading to the same discrete energies as postulated by MILLIKAN and collaborators. *This argument is, however, erroneous.* First, it is unlikely that just *two* mesons will be created, because, as discussed by HEISENBERG,[2] the processes with higher multiplicity must be expected to be practically just as probable as the two-meson process. Secondly, whether this is true or not, the mesons will at any rate obtain relativistic velocities and in that case the electrons emitted by the radioactive decay in our coordinate system, due to the Lorentz transformation, will have energies nearly uniformly distributed between 0 and the *whole* meson energy, as previously stated (p. 22),[3] but overlooked by KLEIN. Any such process will thus lead to *continuously* distributed electron energies and not to the band structure postulated by MILLIKAN and col.

Next, as regards collisions between *unlike* nuclei with x ordinary and y reversed nucleons respectively ($x < y$), or vice versa, KLEIN assumes that $2x$ of the nucleons are completely annihilated and that, due to the thermal energies of the colliding particles being small compared with the binding energies of the nuclei, this annihilation energy will, by a sort of internal conversion of either the photons or the mesons produced, be transferred to the remaining $y-x$ nucleons rather than be given off. KLEIN next assumes this heating up to be so violent that all the $y-x$ nucleons are emitted with *equal* energy.

[1] We only wonder whether these figures may be extrapolated to be valid for the inter*galactic* space, as they have, so far as we know, only been deduced experimentally in the inter*stellar* space.

[2] HEISENBERG 1943 p. 115.

[3] Cf. the detailed calculation in EULER and HEISENBERG (1938) § 14.

Just as was the case for the collisions between like nuclei, KLEIN thus assumes the collisions between unlike nuclei to lead to discrete energies. *This last assumption is, however, certainly just as erroneous as the first one,* because the energy must necessarily be distributed more or less at random over the $y - x$ nucleons, thus again giving a *continuous* spectrum extending up to $2x$ atomic units ([3] p. 33). After some time the neutrons and antineutrons produced by these unlike collisions will, furthermore, decay, being transformed into protons + negatons and negative protons + positons, respectively. Due to the Lorentz transformation mentioned above these particles will again have *continuously* distributed energies extending up to some 10^9 e.v.

We may thus conclude that KLEIN's *hypothesis does not lead to a band structure of the primary radiation,* which on his hypothesis consists of electrons (perhaps photons) together with both positive and negative protons having continuously distributed energies of the order of magnitude of some 10^9 e.v. (the maximum energy at any rate not exceeding the rest energy of Si^{28}, i. e. 26×10^9 e.v.). Furthermore, this primary radiation will obviously consist of practically the same number of positons and negatons as well as of positive and negative protons. *Apart from the electrons (perhaps photons),* which particles must necessarily, as far as we can see, constitute a non-negligible part of the primary radiation, KLEIN's *hypothesis just leads to the same result regarding the primary component of cosmic radiation as our analysis of all the experimental data on the behaviour of the radiation in the atmosphere of the earth.* The crucial point for KLEIN's hypothesis is thus, whether the experiment of SCHEIN, JESSE and WOLLAN[1] is compatible with the existence of a certain electron component in the primary radiation or not. We note, however, that primary photons will *not* be measured in this experimental arrangement and perhaps, therefore, we have to assume the photon rather than the meson annihilation (case (a) above, p. 36). On the other hand, it is impossible at the present state of quantum theory to evaluate quantitatively the cross sections for the various processes in question and thus to estimate the fraction of the primary radiation, which

[1] SCHEIN, JESSE and WOLLAN (1941 a).

according to Klein's hypothesis must be electrons (perhaps photons). Roughly one would expect the fraction originating from the collisions between like nuclei to be of the order of magnitude 10 %, because the most frequent collision leading to electrons is the He-He process,[1] the relative frequency of which is of the order of magnitude $10 \times 10 = 100$, which is just 10 % of the relative frequency of the most frequent collision leading to nucleons, viz. the H-He process, the relative frequency of which is of the order of magnitude $100 \times 10 = 1000$. Hereto must, certainly, be added those electrons originating from the radioactive decay of the neutrons and the antineutrons, but as the energy hereby liberated is only of the order 10^6 e.v., these electrons will in our coordinate system practically move with the same velocity as the neutrons, i.e. their energy will only amount to the fraction $\frac{m}{M}$ of that of the nucleons. Consequently these electrons may be entirely neglected.

Another crucial point for Klein's hypothesis, if it is to explain *all* the primary radiation, is, as stated by himself, whether it is reconcilable with the existence of the large Auger showers, representing a total energy of the order of magnitude of 10^{15} e.v. at sea level, which energy is by several powers of 10 beyond the upper limit represented by the rest energy of Si^{28}, viz. 26×10^9 e.v. We have already above (p. 31) discussed Klein's suggestion for solving this problem, and his rough quantitative analysis does not seem to be unreasonable. This point cannot, however, be decided at present; it must be left for future investigations.

Summarizing, we may say that only further experimental investigations can at all decide on the truth of Klein's hypothesis. We can only say at present that *it seems at any rate very*

[1] We note that also the most frequent collision between like nuclei, the H-H process, may in fact lead to electrons with energies above the lower limit $1{\cdot}4 \times 10^9$ e.v. caused by the blocking effect of the sun. Although a two-photon annihilation can only lead at most to the energy $0{\cdot}9 \times 10^9$ e.v., and the same applies to the electrons resulting from a two-meson annihilation, an annihilation process of 3 or more mesons may lead to electrons of energies of the order of magnitude of 2 atomic units $= 1{\cdot}8 \times 10^9$ e.v. As this is, however, only the case if one of the mesons gets practically the whole energy and the same applies to its decay electron, we suppose such a process to be of negligible frequency in spite of the fact that the relative frequency of the H-H collision is of the order of magnitude $100 \times 100 = 10\,000$.

promising, since it is a conspicuous fact that the energies of the primary cosmic radiation lie essentially within the region of the annihilation energies of the lighter nuclei known to exist in interstellar space ([1] p. 36). Whether *all* the primary cosmic radiation can be explained in this way or we have to explain some part of it by other processes it is premature to decide at the moment.

Summary.

In this paper we discuss the three main problems of present cosmic ray physics, the origin of the radiation, the composition of the primary component, and the genesis of the various components observed in the atmosphere, at sea level and at great depths. In part 1 we review all the experimental data bearing upon these problems. In part 2 we discuss the three possible hypotheses regarding the primary radiation which involve only particles known at present: (I) the electron hypothesis, (II) the proton hypothesis, and (III) the combined electron-proton hypothesis. It proves that the present total experimental evidence cannot be reconciled with any of these hypotheses. For this negative result the crucial arguments are the experiments of Johnson and Barry, of Schein, Jesse and Wollan, the latitude effect of the soft component at great altitude and, finally, the neutrality argument of Swann, which is necessary for the propagation of a charged radiation in interstellar space. There is thus indirect evidence of the existence of a new hitherto unknown particle in the primary cosmic radiation. In part 3 we discuss the hypothesis, put forward by the author and by Klein, that these new particles are negative protons. It is shown that the results of this hypothesis, together with plausible assumptions regarding the genesis of the soft and the hard components, seem to fit extremely well with all the experimental data. Finally, we discuss in part 4 a related hypothesis of Klein, that cosmic rays are produced by the annihilation of ordinary and reversed matter consisting of negative protons, antineutrons and positons.

In the discussion it is emphasized that the present experimental material is still rather incomplete. Especially we need more know-

ledge of the latitude and the east-west effects of the hard and the soft components *separately*, and the dependence of these effects on altitude, latitude and zenith angle, together with the transition from SCHEIN, JESSE and WOLLAN's curve to that of PFOTZER. Only such new experiments can decide whether the purely tentative hypotheses, on the existence of negative protons as well as on the cosmic radiation being produced by annihilation processes, contain part of the truth or perhaps even the whole truth of the genesis of cosmic rays.

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