73. ON A PHYSICAL THEORY OF THE SOLAR CORONA

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SUMMARY

The paper presents a 'Physical Theory of the Solar Corona' based on the discovery of Grotrian and Edlen that the coronal lines are due to forbidden transitions of atoms of iron, nickel and calcium, stripped of a large number of electrons, and presenting the electron-composition $(3p)^x$ ($x=1$ to 5) for iron and nickel, $(2p)^x$ for calcium. It is shown that such ions can be due to some kind of nuclear reaction only, similar to Uranium Fission, occurring at some depth below the chromosphere and they are not certainly due to large scale meteor flashes. The range and energy balance of such high speed particles (*i.e.* the cross-sections for loss of electrons, and capture of electrons from solar atoms) are calculated and discussed. It is shown that they are in good accord with observed facts. The formation of the outer corona is suggested to be due to the constant stream of δ-rays ejected from the solar atoms by the high speed ions. A programme for further work is indicated.

§ 1. INTRODUCTION

The problem of the solar corona has baffled astronomers and physicists ever since physical science began to be applied for an understanding of its mechanism. The available knowledge, and the different theories up to 1936 are summarised in the *Handbuch der Astrophysik*, Band IV, p. 315, and Band VII, p. 395, and subsequent theoretical attempts are given in the references under the headings Anderson (1926), Minnaert (1930), Grotrian (1931 and 1934), and Thackeray (1940). It will be seen from a perusal of these references that there are two distinct but associated problems involved which may be termed respectively as:—

(1) The problem of the Coronium.
(2) The problem of the Corona.

In the Coronium problem, we have to find out the element or elements responsible for the lines 5303, 6374, and others (*vide* Table 1) which are found to occur in the inner corona (from the top layers of the chromosphere up to heights of 5′ to 8′ from the disc), and which used formerly to be ascribed to a hypothetical element 'Coronium'; and the nature of electronic transition giving rise to these lines.

It is now needless to add that all previous speculations regarding the origin of the coronal lines proved to be wrong. The right clue to identification of the origin of the lines was suggested by Bowen's discovery that the nebulium lines can be traced to forbidden transitions of once or multiply ionised light atoms. It was felt that the coronal lines would be found to have a similar origin. The author of the present paper, and probably many others spent considerable time in ransacking the available literature for forbidden lines of elements which may coincide with some of the coronal lines, but without the least success.

The hunt was confined to only singly and doubly, and sometimes trebly ionised atoms, because it was considered improbable that more highly ionised atoms can, without violating ordinary laws of physics, occur in the corona. It was therefore a matter of some surprise when Grotrian, in 1937, announced that the red corona line 6374 had a frequency which was nearly coincident with the frequency difference between the ${}^2P_{\frac{3}{2}}$ and ${}^2P_{\frac{1}{2}}$ terms of $Fe^{+9} \ldots 3p^5$, which has a chlorine-like structure, and the faint infra-red line 7892 had the frequency corresponding to the difference ${}^3P_2-{}^3P_1$ of $Fe^{+10} \ldots 3p^4$. This identification was not taken very seriously at the time, because we cannot see how, if the laws of physics continue to hold good, we can have iron atoms stripped of as many as nine or ten electrons occurring in the inner corona. But the clue was taken up by Dr. Bengt Edlen (Russell, 1941), and he has succeeded in tracing the most important coronal lines to forbidden transitions of highly stripped medium-weight atoms, viz. to Fe^{+9}, Fe^{+10}, Fe^{+12} and Fe^{+13} possessing $3p^5$, $3p^4$, $3p^2$, $3p^1$ structures; and stripped ions of Ni and Ca having similar structures. Details of this identification, as far as available, are given in Tables 1 and 5. The claim is considered a good one by Prof. H. N. Russell, Dr. D. B. Menzel, and other Harvard astrophysicists. It may be mentioned here that these 'lines' have not been actually produced in the laboratory[1], only their frequencies have been calculated from the term-values obtained from the spectra of highly stripped atoms. The author of the present note along with Mr. D. Kundu has re-examined all the published data, and finds no reason for doubting the identification. It appears therefore almost certain that the problem of the origin of the coronal lines has been finally

[1] In fact none of the nebular lines has yet been actually observed in any laboratory experiment. Only the green auroral line 5577 due to $O\ldots 2p^4\ {}^1D_2-{}^1S_0$ has been obtained in the laboratory.

TABLE 1

Lines in the Solar Corona

Wavelength	Frequency	Intensity	Origin	Remarks
3328	30039·46	2·8	..	..
(3359)	29762·24	..	..	..
3388·10	29506·62	44·4	Fe^{+12}...$3p^2$ $^3P_2—^1D_2$	..
3454·13	28942·59	5·6	..	..
(3461)	28885·14	..	..	..
(3505)	28522·54	..	..	..
(3534)	28288·49	..	..	..
3601·00	27762·17	4·4	Ni^{+15}...$3p$ $^2P_{\frac{1}{2}}—^2P_{\frac{3}{2}}$	..
(3626)	27570·76	..	..	..
(3641)	27457·18	..	..	..
3642·9	27442·86	..	..	..
(3648)	27404·50	..	..	..
(3651)	27381·98	..	..	..
3800·8	26302·81	..	..	..
3865	25865·91	..	Fe^{+10}...$3p^4$ $^3P_1—^1D_2$	Bowen (1940) obtains a line at λ 3871·9, and assigns it to the transition given here.
(3891)	25693·08	..	..	..
3986·9	25075·07	0·8	..	..
4086·3	24465·13	1·2	..	..
(4130)	24206·27	..	..	..
(4131·4)	24298·06	..	..	..
4231·4	23626·21	3·2	..	..
(4244·8)	23551·62	..	..	..
4311·0	23189·97	..	Ni^{+11}...$3p^5$ $^2P_{\frac{3}{2}}—^2P_{\frac{1}{2}}$	(?)
4359·0	22934·61	<0·8	Co^{+14}...$3p$ $^2P_{\frac{1}{2}}—^2P_{\frac{3}{2}}$	Identified by D. Kundu (1941).
(4398)	22731·24	..	..	..
(4533·4)	22054·28	..	..	..
4567·0	21890·09	1·2	..	..
4586	21799·40	..	..	..
(4722)	21171·56	..	..	..
(4725)	21158·12	..	..	..
(4779)	20919·04	..	..	..
(5073)	19706·72	..	..	..
5116·03	19540·98	4·8	..	..
5302·86	18852·52	110	Fe^{+13}...$3p$ $^2P_{\frac{1}{2}}—^2P_{\frac{3}{2}}$	Discovered in 1868 by Harkness and Young. See further.
5536	18058·58	..	..	..
(5694·0)	17557·48	..	..	..
6374·51	15683·15	28	Fe^{+9}...$3p^5$ $^2P_{\frac{3}{2}}—^2P_{\frac{1}{2}}$	Discovered in 1914. Identification due to Grotrian (1931*a*).
6704·83	14910·51	3·3	..	Discovered in 1929 by Grotrian (1931*a*).
7059·6	14161·21	4	..	..
7891·94	12667·68	29	Fe^{+10}...$3p^4$ $^3P_2—^3P_1$	..
8024·2	12458·88	1·3	..	..
10746·8	9314·4	240	Fe^{+12}...$3p^2$ $^3P_0—^3P_1$	Discovered by Lyot (1934) by means of the Coronagraph.
10797·9	9261·0	150	Fe^{+12}...$3p^2$ $^3P_1—^3P_2$	,,

NOTE.—The wavelengths are taken from a table given by Dyson and Woolley, *Eclipses of the Sun and the Moon*, p. 132. The intensities are calculated in units of 10^{-6} of the intensity at the same wavelength of photospheric emission, comprised within 1 Å. Lines of doubtful occurrence are given within circular brackets. The identifications as far as they could be inferred from Russell's (1941) short account, and Mr. D. Kundu's investigations are given in column (3). As regards the intensities of the lines, it is well known that they are subject to wide fluctuations. The intensity of the green coronal line 5303 has been found by Lyot (1934) to vary between 3 and 70×10^{-6} of the Fraunhofer spectrum as defined above. The identification of 4359 to Co^{+14}—$1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p$ $^2P_{\frac{1}{2}}—^2P_{\frac{3}{2}}$ is due to D. Kundu (1942) and should be confirmed. Lines due to forbidden transitions of Fe^{+11} are not in the available range.

solved, and the present paper takes up the study from this point onwards.

§ 2. The Corona Problem

The discovery that the 'coronium lines' are due to metastable transitions of very highly stripped heavy atoms considerably enhances the difficulties which have been experienced for the last 80 years in formulating a reasonable physical theory of the 'Solar Envelope'. We use this term in a comprehensive sense after Rosseland (1934), to denote the totality of the phenomena known under the terms: the Reversing Layer, the Chromosphere and the Corona, and consider their problems together as these cannot be dissociated from each other. The composition of the solar envelope is given in Table 2, which is compiled from data given by Unsöld, *Sternatmosphäre* (p. 348). It has not been considered necessary to enter into a critical discussion about the correctness of these values, as the arguments are not likely to be much modified thereby. Full details will be found in Unsöld, *loc. cit.*

Table 2

Element	Reversing Layer	Chromosphere	Inner corona
H-atoms ..	$1{\cdot}8\times10^{22}$	$3{\cdot}6\times10^{20}$	....
O-atoms ..	7×10^{20}	....	....
Metals or C-atoms	7×10^{20}	7×10^{19}	....
Free electrons ..	6×10^{20}	....	7×10^{7} per cm.^{3} at 1′.

The figures under 'Reversing Layer' represent the total number of atoms over one cm.^{2} of the photosphere. Hydrogen and oxygen are taken to be mostly unionised. The metals or C-atoms of Menzel (1931) are taken to be 80% ionised, and the free electrons are the result of their thermal ionisation. The 'Reversing Layer' may have a depth of 100-150 kilometres, over which we have the chromosphere extending over 10^4 km. The number of atoms over 1 cm.^{2} of the base of the 'Chromosphere' (Menzel, 1931) is taken to be roughly 1/1000 of the number in the reversing layer. The inner corona starts from the top of the chromosphere, and show the lines ascribed to 'coronium' usually up to heights of 5′, but occasionally in the case of coronal streamers up to heights of 8′ to 10′ and more. The inner corona also shows a continuous spectrum from which the Fraunhofer lines are absent or blurred out. The outer corona shows a pure continuous spectrum in which the Fraunhofer lines reappear and it extends usually in the quiescent stage up to 15′ but in disturbed times, and in the case of streamers up to several solar diameters.

The continuous spectrum in the inner or outer corona was ascribed by Schwarzschild to Rayleigh scattering of photospheric light by free electrons, and subsequent investigations have confirmed it [Grotrian (1934), Minnaert (1930) and Bumbauch (1937)]. The number of free electrons at different heights is calculated by Minnaert (1930) from photometric measurements of the intensity of the continuous coronal light at different heights. The number-density in the quiescent stage is shown in Table 3, but very considerable fluctuations take place occasionally, particularly over coronal streamers.

The Problems of the Solar Chromosphere

The abnormal heights reached by the H, K lines of Ca have been known for a long time to astrophysicists. In recent years quantitative measurements of gradient of density distributions of the different elements have been made by Pannekoek (1928), S. A. Mitchell and E. J. R. Williams (1933), Cillie and Menzel (1935). The figures of the latter are reproduced in Table 4.

The gradients are far smaller than $5{\cdot}44\times10^{-8}$ cm.$^{-1}$ $\left(\alpha=\frac{mg}{kT}\right)$ which is the value for an element of weight unity and for a temperature of 6000°. There appears to be some '*force of levity*' in action. The origin of this has been looked for in Selective Radiation Pressure (Milne, 1925), Electrical

Table 3

ρ ..	1	1·03	1·06	1·10	1·2	1·3	1·4	1·6	1·8	2·0
log N ..	8·66	8·49	8·36	8·19	7·85	7·58	7·38	7·05	6·79	6·57
ρ ..	2·2	2·4	2·6	2·8	3·0	3·5	4·0	5·0	6·0	8·0
log N ..	6·40	6·25	6·13	6·04	5·96	5·80	5·71	5·58	5·40	5·21

Note : ρ, the distance from the sun's centre is given in units of solar radius. Thus $\rho=1{\cdot}03$ denotes 0·48′ from the disc, i.e. nearly 2×10^5 km. from the photosphere. The electron density per cm.^{3} at this point is 3×10^8. It reduces to $\simeq 10^5$ per cm.^{3} at a distance 7 radii, i.e. 5×10^6 km. The table is taken from Unsöld, *Sternatmosphäre*, p. 440, where it is quoted from a paper by Bumbauch (1937).

TABLE 4

Density-Gradient in the Chromosphere

	Neutral		Ionised		Remarks
H	6563	$1 \cdot 54 \times 10^{-8}$ cm.$^{-1}$	..	..	..
He	5876 $1s\,2p\,{}^3P - 1s\,3d\,{}^3D$	0·78	4686	0·30	*Vide* remarks in text
Mg	..	2·50	4481	—	..
Al	3961, 3944 $3p\,{}^2P_{\frac{1}{2},\frac{3}{2}} - 4s^2\,S_{\frac{1}{2}}$	2·77	..	—	..
Ca	4227 $4s^2\,{}^1S_0 - 4s\,4p\,{}^1P$	>2·11	3934 $4p\,2s_{\frac{1}{2}} - 4p\,{}^2P_{\frac{3}{2}}$	1·51	..
Sc	..	—	..	4·20	..
Ti	..	—	..	3·32	..
Cr	..	>2·07	..	1·72	..
Mn	..	2·95	..	1·60	..
Fe	..	2·48	..	1·69	..
Sr	4607 $5s^2\,{}^1S_0 - 5s\,5p\,{}^1P_1$	..	4077, 4215 $5s^2\,S_{\frac{1}{2}} = 5p^2\,P$	1·66	..

Force, etc., Turbulence (McCrae, 1929). But what is most disconcerting is the fact that the density gradient appears to have the same value for elements widely differing in weight, e.g. for Mg. (A.W. = 24), and Fe (A.W. = 58) and is not much larger than that for hydrogen. What 'mysterious forces' reduce the weight of Mg and Ca to almost the same value as that of H is still a problem.

An important constituent of the chromosphere is Helium, which is not observed in the Fraunhofer spectrum but occurs only in the chromosphere as emission lines; though in recent years 10830·3, $1s\ 2s\ {}^3S - 1s\ 2p\ {}^3P$ has been observed by Babcock (1934) as a faint absorption line, and 5876, $1s\ 2p\ {}^3P - 1s\ 3d\ {}^3D$ was observed by Nagaraja Aiyyar to occur as an absorption line in the penumbra of spots. As a matter of fact, Evershed (1898) noted that helium lines tended to vanish as we approach the 'Reversing Layer'. Following this Pannekoek and Minnaert (1928) and Perepelkin and Melnikov (1935) have determined the distribution of He-atoms emitting D_3 and 4471 ($1s\ 2p\ {}^3P - 1s\ 3d\ {}^3D$, $1s\ 2p - 1s\ 4d\ {}^3D$) with height. They observe that the intensity of the lines tend to vanish at the base of the chromosphere, rises to a maximum at a height of 2,500 km. and then gradually vanish, but can be traced up to a height of 7,500 km. Another anomaly discovered by A. Fowler was the occurrence of He^+4686, having an excitation potential of 73-volts in the *lower* chromosphere (2,500 km).

The reversing layer and the chromosphere show plenty of strong lines of Fe, and Fe^+ and some Fe^{++}-lines have been suspected and the excitation of these lines are satisfactorily explained on the theory of thermal ionisation. But no extranuclear process can deprive the iron atom of thirteen, and possibly of more electrons, at least not in the coronal heights of the sun.

Temperatures of the order of 2×10^7 °C. or photoelectric light of wavelength 1 to 10 Å.U. in sufficient strength would be needed. In fact, Prof. H. N. Russell (1941) remarks:—

'It is hard to see how these stripped atoms can maintain so high a degree of ionisation if the corona, as has generally been supposed, contains many free electrons. But apparent difficulties of this sort often turn out to be guide-posts directing to new knowledge.'

We must add to this that the greatest difficulty has been encountered in finding out a source for these electrons. They cannot arise from thermal or photoelectric ionisation as we have then to postulate, in coronal heights, the existence of atoms and ions; this is impossible on dynamical grounds. Reviewing several theories, Minnaert (1930) remarks: 'Anderson has shown that the corona cannot be in equilibrium if the ordinary physical laws are valid. Instead of assuming, as he does, that very hypothetical modified laws must be applied, we may attempt to account for the corona by assuming that it really is not in equilibrium, and *that its particles are continuously projected towards space.*'

We shall see later that Minnaert has been right in giving up the equilibrium theory. We have to find out what forces impel the electrons towards outside space. In fact difficulties of such a serious nature have been encountered in finding out the origin of coronal electrons, that at one time, it was seriously thought that the coronal glow was due to scattering of light quanta by the light quanta themselves. The scattering cross-section for this effect was in fact calculated by Heisenberg and Euler (1934), but was found to have the extremely small value of 10^{-70} cm.^{2} for the average solar radiation. This requires an enormous number of light quanta for the observed effect, and therefore the hypothesis had to be given up.

In addition to the question of origin, the stability of electron clouds in the corona has engaged the attention of physicists, for a cloud of electrons would disperse to nothing in a very short interval of time due to mutual electrostatic repulsion. Anderson at one time pointed out that the presence of an equal number of positrons might ease the situation, but the query about the origin of the hypothetical positrons has never been answered. It is difficult to see how positrons can occur in the corona, for then electrons and positrons would annihilate each other, forming annihilation radiation. There is no indication that such a process ever takes place in the corona.

Another difficulty was pointed out by Moore (1934) and further investigated by Grotrian (1934). Moore showed that though Fraunhofer lines are blurred out from the inner corona, they reappear in the outer corona. Grotrian (1934) found that the continuous spectrum of the scattered radiation from the inner corona shows depressions in regions corresponding to Fraunhofer absorption, but displaced by about 100 Å.U., but the lines appear again in the outer corona. He sought to explain the first of these observations by the hypothesis that electrons in the inner corona are moving outwards with velocities of the order of 4,000 km. (corresponding to a temperature of $4{\cdot}8\times10^5$). But for the reappearance of Fraunhofer lines in the outer corona, he had to postualate the existence of 'Cosmic Dust'.

But Astrophysicists have never been able to understand how cosmic dust of the size postulated by Grotrain can exist at such close proximity to the sun without vaporising completely. The phenomena may as well be explained by the hypothesis that the electrons in the outer corona are, at least partly, nearly at rest.

§3. Preliminary examination of different hypothesis regarding origin of highly stripped atoms in the solar corona.

Two suggestions may be made regarding the origin of highly stripped iron and other atoms in the solar corona.

(1) That the production of highly stripped iron, nickel and calcium atoms is due to the bombardment of the solar atmosphere by 'Cosmic Dust' which is meteoric matter, consisting mainly of elements which occur in great abundance in stony and iron meteorites, viz. Fe, Ni, Ca, Mg, etc. The 'Dust' or 'Meteors' enter the solar atmosphere with a velocity of the order of $6{\cdot}22\times10^7$ cm./sec. (velocity of escape from the surface of the sun) which is much larger than 3×10^6 cm., the average velocity of entry of cosmic particle into the Earth's atmosphere. In the case of the meteors it is well known that these get incandescent by friction in the Earth's atmosphere, and give out characteristic lines of neutral and once-ionised atoms of Ca, Fe, Mg, Si (Millmann, 1933) and other elements that they are composed of. In the sun, it may be assumed that on account of the much higher energy, the elements are stripped off of many of their electrons.

According to this view, the coronal lines are due to large scale meteoric flashes, and are caused by the passage of the sun through a cloud of cosmic dust. This hypothesis is examined in § 4 and found to be opposed to facts.

(2) We can assume that the highly ionised iron and other atoms are being constantly produced somewhere in the solar envelope by some kind of *nuclear* reaction, similar to Uranium Fission, or some other type of nuclear reaction still undiscovered, and projected upwards with energies of the order of millions of volts, through the higher chromosphere. The ion may even start as a bare nucleus, and its passage through the higher chromosphere may be compared to that of an α-particle or better of uranium fission fragments through the cloud chamber. During its passage, the Fe-ion goes on capturing and losing electrons, and ejecting electrons from the atoms and ions it encounters (Ionisation by Collision). The capture of electrons by the Fe-ion is illustrated by the emission of the coronal lines and electrons ejected from higher chromospheric atoms and ions probably from the outer corona.

We may call this the δ-ray theory of the origin of coronal electrons. It appears to be in fair agreement with all that we know of the outer corona; the δ-rays, i.e. electrons liberated by the heavy Fe and other ions will have a maximum velocity of twice the amount possessed by the original ions and can therefore rise to four times the height of the ions, and thus we require no heavy ions or atoms for the production of the electron atmosphere which gives rise to the outer corona.

If this view be correct, the solution of the coronium problem has also led to that of the corona problem.

§4. Critical examination on the meteor flash hypothesis.

Whether the emitters of Coronal lines are streaming in or streaming out.

Decision may be arrived between the two views by finding out whether the emitters of coronal lines are streaming out or streaming in. Fortunately, we are in a position to give a definite answer to this point.

Grotrian (1931*a*) was the first to find out that the coronal line 5303 has a rather large breadth (of the order of 1 Å.U.). This has been confirmed by Lyot (1934 and 1936) in his Coronagraph observations and he finds for the three most prominent coronal lines the following half-breadths:—

Line.	Half-breadth.	Ratio.
5303	0·80	$1{\cdot}50\times10^{-4}$
6376	0·97	$1{\cdot}52\times10^{-4}$
6703	1·07	$1{\cdot}60\times10^{-4}$

If these breadths are due to Maxwellian motion, the mean velocity is 32 km. per second. Lyot was under the impression that the lines were due to oxygen and he deduced that this signified a temperature of $6{\cdot}6\times10^5$ degrees C. Taking the emitters to be iron-ions, the temperature ought to be $2{\cdot}34\times10^6$ degrees. Such temperatures are of course unthinkable on the surface of the sun, and Waldemeier (1938) has shown that the width curve of Lyot can be explained on the supposition that the emitters of coronal lines are streaming radially outwards with a mean velocity of 60 km. per sec. Lyot (1934, see Fig. 5) has further found that the width is largest when the emitters are nearest the sun's limb, and becomes narrower as the height increases. This combined with Waldemeier's suggestion points out that the velocity of atoms emitting coronal lines increases inwards, i.e. towards the solar limb.

Let us now try to interpret these facts. Waldemeier's suggestion is quite in agreement with Minnaert's quoted above (page 296, right coloumn, line 26). Further, though his conclusions hold equally well whether the emitters are streaming in or streaming out, the fact that they have a mean velocity of the order of 60 km. per sec. in the inner corona shows that they cannot arise from the ionisation of meteoric matter coming from space. In that case the velocity of entry would be of the order of 600 km./sec. It may be supposed that this velocity diminishes in the inner corona to 60 km. on account of the resistance, but this is not very probable, because, the resisting force would be working far more strongly as the particles plunge inwards, and the velocity would therefore diminish inwards. This is irreconcilable with Lyot's finding that the velocity of the emitters is largest nearest the sun's limb, and diminish outwards.

Russell (1929) considered the dynamics and physical state of meteoric matter near the stars, particularly the sun. His conclusion may be quoted:

'Masses of stone or iron will be completely volatilised by the sun's heat, before they reach the surface, unless they were originally a foot or more in diameter. But the atoms resulting from volatilisation will proceed with unaltered speed, and fall into the sun unless repelled by radiation pressure.... Further, the meteoric matter falling into the sun may scatter enough to account for a small fraction of brightness of the corona, but cannot exert enough effective absorption in the spectrum to produce the equivalent of a single narrow Fraunhofer line' (equivalent width 10^{-3} Å.U.).

It can be easily seen that an iron-atom moving through the sun's atmosphere with a velocity of 6×10^2 km./sec. cannot lose any electron by collision with the free electrons of the upper corona, for the effect is the same as if the iron-atom was at rest, and the electrons were moving past it with a velocity of 6×10^2 km./sec. For an electron, the equivalent energy is merely one-electron volt and is too low to cause even the loss of a single electron from the Fe-atom. It would be otherwise in case of collision with protons, or heavier nuclei (say α-particle or heavier ions). In the case of encounter with protons, it is equivalent to bombarding the iron-atoms with protons of about 2,000 volt energy, and about 13 collisions are sufficient to relieve the iron-atom of 13 electrons. But neither hydrogen lines nor lines of any other familiar elements have been observed beyond a height of 14,000 km. (top of the chromosphere), and as Anderson (1930-1932) has shown it is dynamically not possible that any atom or ion can, under the usual conditions prevailing in the sun, rise to the height of the inner corona (i.e. from the top of the chromosphere to a height of 3′ to 5′, i.e. $1{\cdot}30\times10^5$ to $2{\cdot}17\times10^5$ km.). It is therefore almost certain that an iron-atom vaporised from a meteor striking the sun with the usual velocity cannot be relieved of as many as 13 or 14 electrons while passing to *the inner corona*. We must look for the origin of these highly stripped atoms elsewhere.

§ 5. Nuclear reaction theory of coronal excitation.

We shall now develop the ideas of nuclear reaction theory of coronal excitation briefly sketched in § 3. It may be mentioned here that there is already a certain volume of opinion in favour of such a view. Thus Rosseland (1933), after reviewing at length the numerous anomalous results in the solar envelope, points out that some of these anomalies may be explained, by assuming that some kind of radioactive process is in action, *which forces charged particles radially outwards through the envelope*. Naturally enough, no attempt was made to define the nature of this radioactive process, and the reaction of the charged particles with the atoms and ions on the solar envelope.

From the evidence so far available, forbidden lines of Fe^{+9}.... Fe^{+13}, having the constitution $2p^x$ ($x=5$ to 1), and lines of Ca and Ni having similar constitution have been identified in the corona. It is quite possible that there may be still more highly charged Fe^+-ions, viz. Fe^{+14} ($3s^2$), Fe^{+15} (....$3s$), Fe^{+16} ($2p^6$). But as these have no metastable levels, there are no means of detecting their presence in the corona. Fe^{+17} ($2p^5$) does not appear to have been yet spectroscopically investigated, but on extrapolation from known data, the forbidden line $^2P_{\frac{3}{2}}-{}^2P_{\frac{1}{2}}$ is expected to have a wavelength of 900 Å.U. This being in a region not available to observation the presence of Fe^{+17} cannot be detected. It can be proved that no other ion of higher charge can emit a metastable line within visible range; hence even if they are present in the corona or lower, in the solar envelope, it is not possible for us to detect their presence.

We shall now give certain arguments which appear to point out that the probability of occurrence of ions more highly stripped than Fe^{+16} or Ni^{+18} is extremely small. For this purpose, we refer the reader to Table 5, in which the ionisation potentials of iron, as far as available, are given.

A glance at Table 5 shows that the ionisation potentials of Fe-ions from Fe^{+8} to Fe^{+15} corresponding to the removal of electrons from $3p$, and $3s$-shells, vary in continuous gradation from 233 volts to 487 volts. There is a sudden jump at Fe^{+16} ($2p^6$) where the I.P. jumps up to 1250 volts. This is as expected, because now the electron has to be detached for the first time from the $2p$ shell. We calculate the orbital velocities of electrons in the different shells on the assumption that $V=\sqrt{\frac{I.P.}{13\cdot56}}\,cf$, where c=velocity of light, f=Sommerfeld fine-structure constant, cf=velocity of the electron in the H-atom. We find (*vide* column 5 of Table 5) that z_i/n varies from 4·15 for Fe^{+8}. . $3p^6$ to 5·99 for Fe^{+15}. .$3s$ in a continuous sequence, but suddenly jumps to 9·65 cf for the next ion Fe^{+16}.

TABLE 5.

Stripped Iron-ions and their Electron-Structure, etc.

Ion	Electron Structure	Fundamental State	Value of the lowest terms in volts	$\sqrt{\frac{I.P.}{13\cdot54}}=\frac{z_i}{n}$	Remarks
Fe^{26}I	$..3d^6\,4s^2$	$^5D_4$	7·83	0·76	..
Fe II	$..3d^6\,4s$	$^6D_{4\frac{1}{2}}$	16·5	1·10	Forbidden lines found in η-Carina. Bowen (1936)
Fe III	$..3d^6$	^5D	30·48	1·50	..
Fe IV	$..3d^5$	^6S	56·8	2·05	..
Fe V	$..3d^4$	$^5D_0$	..	(2·37)*	Bowen (1940) gives metastable lines found in nebulae. D. Kundu thinks that some of these lines may occur in the corona.
Fe VI	$..3d^3$	$^4F_{\frac{3}{2}}$	..	(2·69)	,,
Fe VII	$..3d^2$	^3F	..	(3·01)	,,
Fe VIII	$..3d$	^2D	150·4	3·33	$^2D_{\frac{3}{2}}-{}^2D_{\frac{5}{2}}=1875$ cm.$^{-1}$ No metastable line available.
Fe IX	$..3p^6$	$^1S_0$	233·5	4·15	No metastable state.
Fe X	$..3p^5$	^2P	261	4·39	λ 6374·75 $^2P_{\frac{3}{2}}\leftarrow{}^2P_{\frac{1}{2}}$
Fe XI	$..3p^4$	^3P	288·9	4·62	λ 7892
Fe XII	$..3p^3$	^4S	320	(4·91)	Has no metastable line in the available range.
Fe XIII	$..3p^2$	$^3P_{012}$	346	(5·06)	10746·80, 10797·95 }
Fe XIV	$..3p$	^2P	373	5·25	λ 5303 $^2P_{\frac{1}{2}}-{}^2P_{\frac{3}{2}}$
Fe XV	$..3s^2$	$^1S_0$	454	5·79	No metastable state.
Fe XVI	$..3s$	$^2S_{\frac{1}{2}}$	487	5·99	,,
Fe XVII	$..2p^6$	$^1S_0$	1259·7	9·65	,,

*Parentheses ( ) denote that the value is extrapolated.

In a Uranium Fission process the fragments are formed with energies of the order of 80 to 100 mev. (mev=million-electron-volts). Elements like Fe and Ni can be formed only in a threefold or fourfold fission process, of heaviest elements Ur^{239}, Ur^{235}, Prot. $Act.^{231}$, or Th^{232}, which alone, according to Bohr and Wheeler (1939) are capable of fission. These processes, however, have not yet been observed, but are quite possible on energetic grounds.

If an iron-atom is formed in such a process, its kinetic energy will be of the order 60 mev., corresponding to a velocity of 6·4 *cf.* If the velocity is 10 *cf* the energy would be 140 mev., which is impossible on energetic grounds. Let us now ask what will be the number of electrons which will be retained by the fission-fragment ? Now Bohr (1940, 1941), Knipp and Teller (1941), and Lamb (1941) have discussed this point in connection with the problem of finding out the net charge carried by a fission-fragment and have shown that the number of electrons retained is limited by the condition that the orbital velocity of the outermost electrons retained by the ion, i.e. V_e should be larger than that of the fragment as a whole, viz. V_i where $\frac{1}{2}M.V_i^2$=energy of fission. This points out that the fission fragment can be at most Fe^{+15}, but not Fe^{+16}. As Fe^{+15}. .3*s*, and Fe^{+14}. $.3p^6$ have no metastable levels, they cannot be detected. We can detect ions ranging from Fe^{+13}. .2*p* to Fe^{+9}. $.2p^5$, as already noted by Russell (1941).

§6. Passage of Highly Charged (Stripped) ions Throufh the Solar Envelope.

In this section, the passage of highly charged iron-ions through the solar envelope will be considered. To start with, we do not make any *a priori* assumption regarding the exact point where the stripped ions originate, but merely assume that it happens somewhere in the reversing layer. As a first approximation we consider the envelope to consist mainly of H-atoms, in accordance with considerations given in § 2.

The various possible reactions of a highly stripped iron atom with H-atoms in the solar envelope are:

(1) That the Fe-ions, etc., release electrons from the H-atom by the process known as ionisation by collision [Thomson (1930), Bohr, Bethe (1932), Bloch (1933)].

As we shall see presently, this is the main factor for the reduction in energy of the ion.

(2) When the velocity slows down, due to electron-capture, there may be liberation of the proton (nuclear process).

The loss due to this effect is usually of the order of 10^{-3} times the first, but may be comparable when $V_i \simeq cf.$

(3) The ion may have its charge reduced by capture of free electrons, or electrons from the H-atom.

This process must be taking place in the reversing layer and the chromosphere, and as a result, the Fe-ion goes on losing its net charge as we actually observe (Fe^{+13} to Fe^{+9}).

Energy loss due to ionisation by collision.

The energy-loss of the Fe-ion due to liberation of an electron from the H-atom is given by Livingstone and Bethe, 1937

$$-\frac{dE}{dx}=\frac{4\pi ne^4 z_i^2}{mV^2}\, ln\left(\frac{2mV^2}{I}\right), \tag{1}$$

where E=energy of the particle=$\frac{1}{2}MV^2$,

z_i=effective charge of the ion,

I=average excitation potential of the H-atom.

The effective charge of the Fe-ion varies from z_i=6 for Fe^{+15} to z_i=4 for Fe^{+8}. We shall, in the first instance, assume z_i to have the average value 5.

The quantity I is not the Ionisation Potential $\frac{2\pi^2e^4m}{h^2}=I_0$, but is=$yI_0$, for particles are usually released with some velocity. The value of y has been found experimentally for N_2, O_2, H, A (Lehmann, 1927), but naturally no experiment can be carried out for H. We have taken y=2, and y=1·2 rather arbitrarily.

After some work, the formula (1) can be put in the form

$$-\frac{dE}{dx}=n.\sigma_e mc^2, \tag{2}$$

where σ_e may be called 'the electron-release cross-section' and is given by

$$\sigma_e.=2\pi r_0^2 z_i^2\left(\frac{Mc^2}{E}\right)\left\{lnE+ln\left(\frac{4m}{MyI_0}\right)\right\}, \tag{3}$$

where $r_0=\frac{e^2}{mc^2}$=nuclear radius.

Expressed in electron-volts, we have

$$\sigma_e.mc^2=8{\cdot}37.10^{-7}.\ \frac{\log E-5{\cdot}858}{E}.\ \text{ev. cm.}^2 \tag{3a}$$

In using this formula, E should be expressed in electron-volts. A plot of log σ_e against log E is given in Fig. 1.

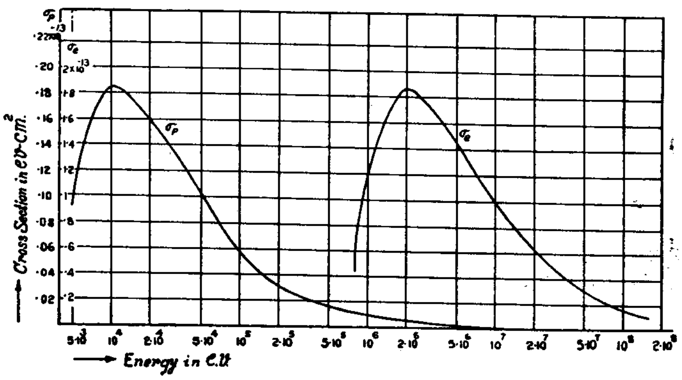

Fig. 1 Electron-release cross-section (σ_e) and proton-release cross-section σ_p of a stripped iron atom at different energies (z_i=5, y=2).

Energy-loss due to proton-release.

Let us next find out the energy-loss suffered by the ion due to communication of energy to the proton. According to Bohr (1940) this is given by:—

$$-\frac{dE}{dx}=n.\sigma_p.mc^2, \qquad .. \qquad .. \quad (4)$$

where σ_p =proton-release cross-section and is given by:—

$$\sigma_p.mc^2=\frac{4\pi e^4 z_1^2 z_2^2}{M_2 V^2}.\ ln\left(\frac{M_1 M_2}{M_1+M_2}\cdot\frac{V^2.a_{12}}{z_1 z_2 e^2}\right), \qquad .. \quad (5)$$

where z_1 .. Charge of the ionising particle; here z_i.
z_2 .. „ „ „ nucleus of atom; here=1.
M_1 .. Mass of the particle, i.e. of Fe-ion.
M_2 .. „ „ „ atom; here M_H
a_{12} .. Effective radius of collision.

Since $M_2=M_H$ (mass of proton), and $M_1=58\ M_H$, we can put

$$\frac{M_1 M_2}{M_1+M_2}=M_2=M_H.$$

$$a_{12}\simeq a_B\left((\text{Bohr-radius}=\frac{h^2}{4\pi^2 e^2 m}\right).$$

After some work, it can be shown that

$$\sigma_p=2\pi r_0^2\,\frac{m}{M_H}\cdot z_i^2\left(\frac{Mc^2}{E}\right)\left[lnE+ln\left(\frac{M_H}{Mz_iI_0}\right)\right]. \quad .. \quad (6)$$

In deducing this formula, we have made use of the relation $e^2/a_B=2I_0$.
Expressed in electron-volts, the expression reduces to

$$\sigma_p.\ mc^2=4{\cdot}56\times10^{-10}\left\{\frac{\log E-3{\cdot}594}{E}\right\}\ \text{ev. cm.}^2 \qquad (6a)$$

A plot of log ($\sigma_p.mc^2$) against log E is shown in Fig. 1. It is easily seen that σ_p is about $\frac{1}{2000}\ \sigma_e$, at high values of E, but the two become comparable when $E\simeq10^6$ ev.
We have in fact

$$\frac{\sigma_e}{\sigma_p}=\frac{m_H}{m}\left(\frac{\log E-5{\cdot}858}{\log E-3{\cdot}594}\right).$$

Formula (3*a*) is inapplicable when E is $<10^6$ ev. We have then $V_i\simeq0{\cdot}8$ *cf*, i.e. Fe-ion will by this time acquire electrons, the value of z_i would go down, and formula (3*a*) ceases to apply.

Depth of the Layer which can be penetrated by the Fe-*ion.*

We shall now calculate 'the Range' of the highly stripped ions in the solar envelope. The results of the calculation are rendered somewhat uncertain by the fact that we have to choose z, and y rather arbitrarily. But this is unavoidable at the present stage.

Following a procedure adopted by P.C. Bhattacharyya (1941), (1) can be put in the form

$$n\ dx=-\frac{My^2}{128\pi mz_i^2}\cdot\frac{1}{a_B^2}\cdot\frac{d\epsilon}{ln\ \epsilon}. \qquad .. \quad (7)$$

where a_B =Bhor-radius$=\frac{h^2}{4\pi^2e^2m}$, $\epsilon=\left(\frac{4m}{M}\cdot\frac{E}{yI_0}\right)^2$.

We can as a preliminary measure neglect the other causes of energy loss. These are: losses due to proton release, to gravity, and to collisions with other atoms, viz. Oxygen and C-atoms. We take $z_i=5$, $y=2$; we can then apply (7) to find out the number of H-atoms which the Fe^+-ion can traverse before it loses its energy. We obtain

$$\int n\ dx=N(x_0)-N(x)=\frac{My^2}{128\pi mz_i^2}\cdot\frac{1}{a_B^2}\int_{\epsilon_0}^{\epsilon_{max}}\frac{d\epsilon}{ln\ \epsilon}$$

$$=1{\cdot}46\times10^{18}\left[E_i(\log\epsilon_m)-E_i(\log\epsilon_0)\right] \qquad (8)$$

For E_m=60 mev., $\epsilon_{max}=(83{\cdot}26)^2$, log $\epsilon_m=8{\cdot}833$, E_i(log ϵ_m) =900 in round numbers.
Let us take the lower limit E_0=1 mev., corresponding to $V_i=2\times10^8$ cm./sec. $\simeq$*cf*. At this stage, the Fe-ion will have captured electrons from the H-atom, and would have most of its charge neutralized. $E_i(\log\epsilon_0)=0$, i.e. the formula (8), is inapplicable at this stage.

We find that with these assumptions

$$N=\int n\ dx=1{\cdot}3\times10^{21}, \qquad .. \qquad .. \quad (9)$$

i.e. an Fe^+-ion of net charge $z_i=5$ and hav ing an initial energy of 60 mev. can pass through $1{\cdot}3\times10^{21}$ H-atoms before it loses the whole of its energy by electron-release. A reference to Table 2 shows that this is 1/15 of the number of H-atoms over the photosphere. Hence the Fe-ion has to originate rather high up in the reversing layer, but far below the base of the chromosphere. If the Fe-ion has to originate on the photosphere, a rough calculation shows that E_m should be 280 ev., and V_i=13 *cf* and the iron-ion should be Fe^{+22}. . . . $1s^2$. $2s^2$.

The probable value of 'y' in the case of different gases has been considered by Rutherford, Chadwick and Ellis (*Radiations for Radioactive Substances*, p. 81, Table). For diatomic gases the experimental value of y=2, and for monatomic gases, we have for He, y=1·13, for Ne, A, Kr, y=1·3, 1·6, 1·75, respectively. Atomic hydrogen resembles He most, as it has the smallest number of electrons next to He, and its radiation potential is high like He. A value of y=1·12 is likely therefore to be more correct for H-atoms.

Taking this value of y, we get

$$\sigma_e=8{\cdot}37\times10^{-7}\,\frac{\log E-5{\cdot}606}{E}\text{ev. cm.}^2 \qquad (10)$$

i.e. the constant is 5·606 instead of 5·858 in formula (3*a*).

Putting this value of y in the formula for calculation of range, we find that

$$\int n\, dz = 4{\cdot}74 \times 10^{17} [E_i(\log \epsilon_m) - E_i\,(\log \epsilon_0)]. \qquad (11)$$

The value of ϵ's, however, is different. For $E=60$ mev., $\log \epsilon_m = 9{\cdot}987$, and $E_i\ (9{\cdot}987) \simeq 2400$; the value of E_0, the lowest energy at which the formula ceases to hold now becomes 5×10^5 volts. We have

$$N = 1{\cdot}12 \times 10^{21} \qquad (12)$$

so that the total number of particles which can be traversed remain pretty nearly the same.

The value of z_i varies from 6 to 4. In Fig. 2, the

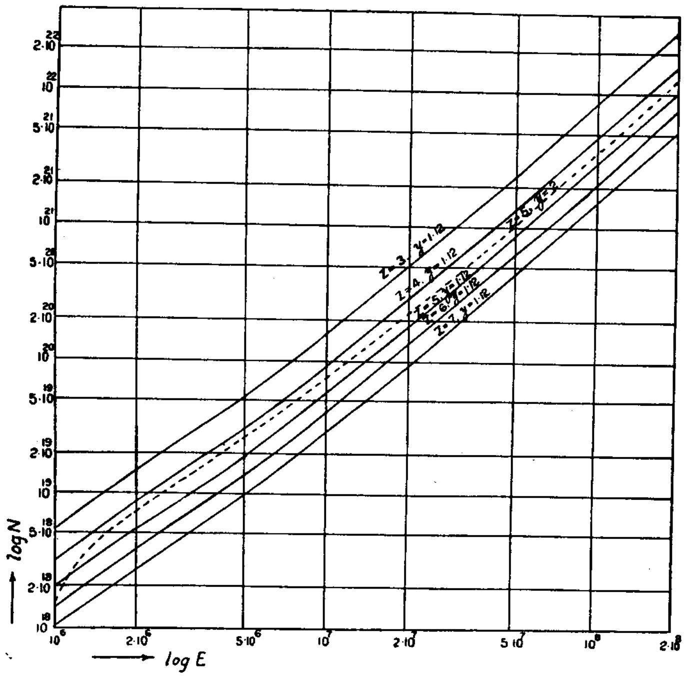

FIG. 2. Total range of a stripped iron atom at different energies for various values of the effective charge. Range has been expressed as the total number of H-atoms traversed.

$\log N/\log E$ curves for different values of z_i, and for $y=1{\cdot}12$, and for $z_i=5, y=2$ are drawn.

§ 7. Capture and Loss of Electrons by the Swiftly Moving Ions.

We have assumed in the foregoing treatment that the iron-ion takes its birth in the reversing layer as an Fe^{+16} $1s^2\, 2s^2\, 2p^6$-ion, with an energy of *ca* 60 mev. and gradually loses this energy on its passage through an atmosphere composed mainly of H-atoms. In course of this passage the ions have a chance of not only capturing free electrons but also electrons from the H-atoms and other atoms and ions; further, it can also lose electrons by collision. Let us now consider this electron exchange phenomena.

The only parallel case in experimental physics is the phenomenon discovered by Henderson (1922) that the α-ray, while passing through the last one cm. of its range in air, can capture an electron from the molecules, and become He^{+}, which then might lose an electron by collision. Rutherford showed that this kind of alternate capture and loss takes place nearly two thousand times during the last 1 cm. of the path of the α-particle. Towards the extreme end of the track, He^{+} may capture an electron and become neutral He, which may again lose an electron by collision. These cases have been treated by Rutherford (1923) and Jacobsen (1930). A preliminary account may be found in *Radiations from Radioactive Substances* by Rutherford, Chadwick and Ellis (p. 124 *et seq.*).

It has been shown by these authors that if $N\,(He^{++})$ be the number of α-particles, $N(He^{+})$ the number of α-particles which have caught an electron, σ_c is the capture cross-section of an electron from air molecules by He^{++}, and σ_l is the loss cross-section of an electron from He^{+}, then we have for equilibrium

$$N(He^{++})\sigma_c = N(He^{+})\sigma_l. \quad \ldots \quad \ldots \quad (13)$$

In place of σ_c, σ_l, we can introduce λ_c, and λ_l, the mean free-paths for capture, and loss. It is clear that $\lambda_c = \dfrac{1}{N\sigma_c}$, $\lambda_l = \dfrac{1}{N\sigma_l}$, where N is the number of air molecules per c.c.

From this relation, we have

$$N(He^{++})/\lambda_c = N(He^{+})/\lambda_l. \quad \ldots \quad \ldots \quad (14)$$

λ_l is obtained from experiments, and λ_c from observed ratios of $N(He^{++})$ to $N(He^{+})$. Kramers and Brinkmann (1930) have developed a theory of capture of electrons from air molecules by the He^{++}-particle, and find that subject to certain assumptions, their results are in agreement with the data given by Rutherford *et al.* Jacobsen (1930) has given a method of calculating λ_l independently.

Let us now turn to the present case. We have supposed that the iron-ion starts its career as an Fe^{+16}. $.1s^2\, 2s^2\, 2p^6$-ion, with a velocity slightly greater than 6 *cf.* Let us calculate first σ_l for any ion, by following the method given by Jacobsen. We can suppose that the ion is at rest, and the H-atoms are rushing past it with the velocity of the ion, V_i, which is slightly larger than 6 *cf.* Then an electron can be knocked out of the Fe^{+16}. $.1s^2\, 2s^2\, 2p^6$ by either the electron of the H-atom or its nucleus. According to the formula developed by J. J. Thompson (1932), the energy communicated to the electron is given by

$$Q = \frac{2E^2e^2}{mV_i^2(p^2+d^2)}, \quad \ldots \quad \ldots \quad (15)$$

where E, M are the charge and mass of the ray (i.e. either the electron, or the nucleus of the H-atom);

e, m are the charge and mass of the electron belonging to Fe^{+16};

p=collision distance.

Case (1);

In the first case (ionisation by electron of the H-atom), $E=e$, $M=m$,

$$\therefore\ Q=\frac{2e^4}{mV_i^2(p^2+d^2)} \text{ and } d=\frac{eE(M+m)}{mMV^2}=\frac{2e^2}{mV^2}.$$

So Q_0 which is the value of Q for $p=0$ and the maximum energy which can be imparted to the electron by the ionising particle equals $\frac{2e^4}{mV^2}\left(\frac{mV^2}{2e^2}\right)^2=\frac{1}{2}mV^2$.

From (15), we obtain

$$2\pi p\ dp=-\pi\frac{dp^2}{dQ}dQ=\frac{2\pi e^4}{mV^2}\cdot\frac{\delta Q}{Q^2}. \qquad \text{.. (16)}$$

The total ionising cross-section is obtained by integrating this expression within the limiting values of Q. These are the maximum energy communicated when $p=0$, and W_i, the energy needed to release an electron from the Fe^{+16}-ion. We have then

$$\sigma_l^e=\frac{2\pi e^4}{mV^2}\left[\frac{1}{W_i}-\frac{1}{Q_0}\right]. \qquad \text{.. (17)}$$

In the case of ionisation by the proton, or any heavy particle it can be shown by a similar procedure that $Q_{\max}=2mV^2=4Q_0$. So we have

$$\sigma_l^p=\frac{2\pi e^4}{mV^2}\left[\frac{1}{W_i}-\frac{1}{4Q_0}\right]. \qquad \text{.. (18)}$$

So we have

$$\sigma_l=\sigma_l^e+\sigma_l^p=\frac{4\pi e^4}{mV^2}\left[\frac{1}{W_i}-\frac{5}{8Q_0}\right]. \qquad \text{.. (19)}$$

Now, if we put $V_i=s.cf$ we have, since $\frac{1}{2}mc^2f^2=e^2/a_B$,

$$W_i=z_i^2\frac{e^2}{2a_B},\ Q_0=\frac{1}{2}mV^2$$

$$\sigma_l=8\pi a_B^2\cdot\frac{s^2-\frac{5}{8}z_i^2}{s^4z_i^2}. \qquad \text{.. (19a)}$$

According to Table 2, we have in the solar envelope 90% H-atoms, 3·5% O-atoms, 3·5% C-atoms, and 3% electrons. The O-atoms have each 8 electrons, and each one of these electrons can ionise the Fe^{+}-ion, and similarly some of the electrons of the C-atoms. So the number n of electrons per c.c. which can ionise the Fe^{+}-ion is given by

$$n=n_H+n_O z_1+n_C z_2+n_e$$

where n_H, n_O, n_C are the number of H, O and C-atoms. n_e=number of free electrons.

Taking z_1, $z_2=8$, we have $n=90+8\times3{\cdot}5+8\times3{\cdot}5+3=150$ nearly for 100 solar atoms.

The number of heavy molecules, on the other hand, remain 100. Hence we have

$$\sigma_l=\sigma_l^e+\sigma_l^A=1{\cdot}50\left[\frac{1}{W_i}-\frac{1}{Q_0}\right]+\left[\frac{1}{W_i}-\frac{1}{4Q_0}\right]$$
$$=2{\cdot}50\left[\frac{1}{W_i}-\frac{0{\cdot}7}{Q_0}\right].$$

So we have the effective cross-section

$$\frac{\sigma_l}{2{\cdot}5}=8\pi a_B^2\,\frac{\{s^2-\alpha z_i^2\}}{s^4z_i^2}. \qquad (20)$$

If we multiply this quantity by n, the number of atoms per c.c.

$$\lambda_l=\frac{1}{2{\cdot}5n\sigma_l}=\frac{1}{20\pi a_B^2}\left(\frac{s^4z_i^2}{s^2-\alpha z_i^2}\right). \qquad \text{.. (21)}$$

Under the assumptions made here $\alpha=0{\cdot}7$, but it can have any value from 0·7 or a somewhat higher value to 0·625 for a purely hydrogen atmosphere.

We have not applied the correction introduced in the ionisation formula by Thomas and E. J. Williams (1933) due to the orbital motion of the electrons as the theory is not yet much developed. The introduction of these corrections may modify the argument substantially.

The value log (σ/a_B^2), for different values of 's' and z_i are shown in fig. 3.

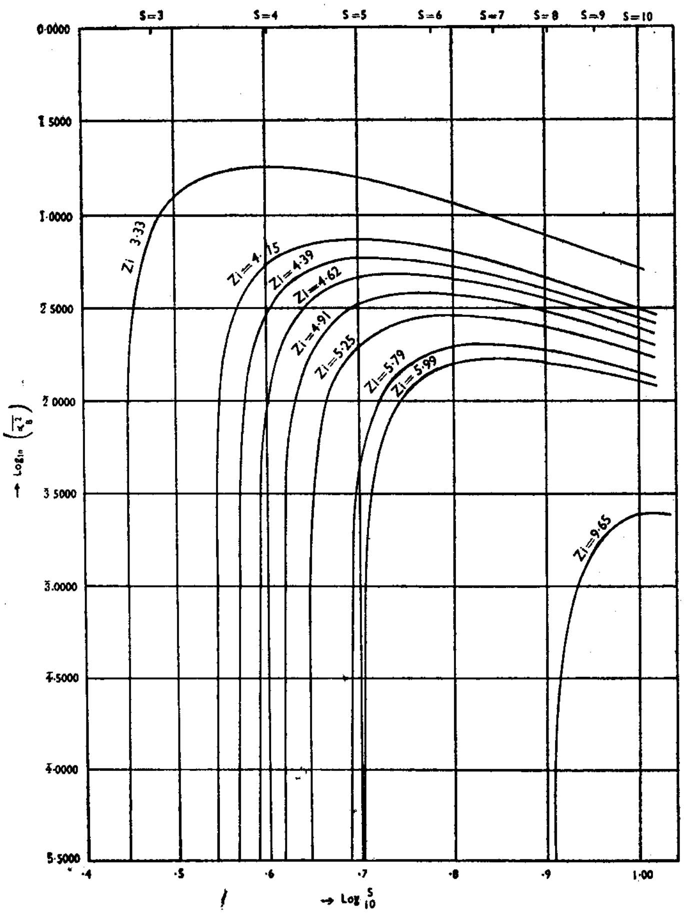

FIG. 3

The general features of these σ_l-curves for the iron-ions may be noted.

We find that there is a critical velocity s_c below which σ_l vanishes. The value of $s_c = \sqrt{\alpha}\, z_i$. These critical values of velocity and the corresponding energies of the iron-ion are given in the second and third rows of Table 6.

TABLE 6

Fe^{+} ..	16	15	14	13	12	11	10	9	8
s ..	8·072	5·010	4·844	4·392	4·234	4·108	3·865	3·673	3·471
E (in mev.) ..	92·26	35·55	33·22	27·32	25·37	23·89	21·14	19·10	17·06
s_m ..	11·41	7·086	6·850	6·212	5·987	5·809	5·466	5·194	4·909
E (in mev.) ..	184·5	71·09	66·43	54·63	50·75	47·77	42·29	38·19	34·12

The maximum value of σ_l occurs at $s=\sqrt{2\alpha}\, z_i$, i.e. at $0{\cdot}99z$, i.e. very nearly at $s=z$. The value of σ_l (called σ_{lm}) at this point is given by $(\sigma_{lm}/a_B^2)=7{\cdot}1\pi/z_i^4$. The value of s_m for the different ions is given in the fourth row of Table 6.

The log (σ_l/a_B^2)—log s curves are drawn in fig. 3. We note that log (σ_l/a_B^2) rise from $-\infty$ (i.e. $\sigma_l=0$) at s_c very steeply to the maximum value at $s_m=\sqrt{2}\, s_c$, and then falls down in a very gentle slope.

Electron-capture by the Fe-*ions.*

In this section, the cross-section for electron-capture by the Fe-ions are calculated. The electron captured may be:—

(1) a free electron,
(2) electron bound to the H-atom in the $1s$-state,
(3) electron bound to the C-atoms, oxygen and other constituents of the solar envelope.

Capture of Free Electrons.

The problem of capture of free electrons by hydrogen-like ions has been very fully treated by Stobbe (1930). He has given tables of the capture cross-sections of free electrons moving with the velocity 'V', relative to a stationary hydrogen-like ion with the charge z_i, the capture being effected in the *ns*, *np*, *nd* orbits.

In our present case, the ion is moving through the solar envelope with the velocity $V_i = c.f.s.$ The velocity of the electrons relative to the Fe^{+}-ion is given by $\vec{V}=\vec{V}_i-\vec{V}_e$, where $\vec{V}_e$ is the velocity of the free electron.

Now $|V_i| >> |V_e|$, hence we can put $\vec{V}=\vec{V}_i$ (*vide* Stobbe's table, p. 687).

Stobbe expresses his capture cross-sections in the form of functions of a quantity x which in our notation $=\frac{ns}{z_i}$, where n is the total quantum number. With the aid of these tables, we can attempt an estimate of the cross-section for the capture of free electrons by Fe-ions.

For Fe^{+16}. .$1s^2\ 2s^2\ 2p^6$, we have $z_i/3=5{\cdot}99$, and 's' may be supposed to vary from 6 downwards. We have, therefore, $x=\frac{ns}{z_i}=1.\ .\ .\ .\ .$to $0{\cdot}16$, the lower limit being for $s=1$. According to Stobbe's tables, σ_{35}(q_{30} in Stobbe's notation) varies from $4{\cdot}06\times10^{-26}$ cm.^{2} to $\simeq5\times10^{-21}$ cm.^{2}

Since there are probably not more than 6×10^{20} electrons in the solar envelope, we see that the probability of capture of free electrons by the Fe^{+16}-ion is extremely small, except when the velocity has fallen to $V_i\simeq cf$. But this takes place in the high chromosphere, where there are not sufficient electrons to capture.

It can be shown in a similar way that the capture cross-section of free electrons by Fe^{+15}. .$3s$ is of the same order.

When we come to the Fe-ions, Fe^{+14} to Fe^{+9}, the capture takes place in the $3p$-orbit. As a first step, the problem may be treated as hydrogen-like, the value of $x=\frac{ns}{z_i}$ being obtained from the known values of (z_i/n), given in Table 5. The value of q_{3p} is obtained from Stobbe's tables (p. 687), it $=q_{31}$ in his notation. At low velocities, these values are larger than q_{3s}, but at high velocities they are smaller. For Fe^{+9}, $z_i/3=4{\cdot}39$, $\frac{ns}{z_i}=0{\cdot}228$, $q_{3p}\simeq5\times10^{-22}$ cm.^{2} Hence the probability of capture of free electrons by Fe^{+}-ions is generally very small.

Case (2).

The general case of electron capture by a swiftly moving ion from any type of ion or atom has not yet been solved. Kramers and Brinkmann (1930) have given a solution of the problem of capture of an electron moving in the s-orbit of some atom by a charged-particle into its own s-orbit, both being regarded hydrogen-like. These results have been applied by them to the data of Rutherford (1923) and Jacobsen (1930) on the capture and loss of electrons by He^{++}-particles with good success.

The capture cross-section from one 1*s*-orbit to another 1*s*-orbit is given by the formula,[2]

$$\frac{\sigma}{a_B^2}=\frac{\pi}{5}.2^{20}.\,z^5\,z'^3.\,s^8/[s^2+(z+z')^2]^5[s^2+(z-z')^2]^5.\;\ldots\;(22)$$

Here the atom-ion is assumed to have the charge z', and moves with the velocity $V=cf.s.$

z=charge on the atom from which the electron is captured.

When the capture is from an 1*s*-orbit to an *ns*-orbit, we have

$$\sigma_n=n^2\sigma_1(z,\,z'/n). \qquad (23)$$

In the present case, the Fe^{+16}-ion is capturing an electron into the 3*s*-orbit from the H-atom, the electron there being in the 1*s*-orbit. We have put $n=3$, $z'/3=z_i$ of Table 5= 5·99, $z=1$. Hence we have for Fe^{+16}

$$\frac{\sigma_i}{a_B^2}=3^2.\frac{\pi}{5}.2^{20}.5{\cdot}99^3.\frac{s^8}{[s^2+6{\cdot}99^2]^5\,[s^2+4{\cdot}99^2]^5}.\quad\ldots\quad(22a)$$

We can apply the same formula for the capture of an electron by the Fe^{+15}... $1s^2.\,2s^2.\,2p^6\,.3s$ thus completing the $3s^2$-shell. We have to put $z_i=5{\cdot}79$. We have then

$$\left(\frac{\sigma_c}{a_B^2}\right)=\frac{3^2.\,\pi.\,2^{20}}{5}.(5{\cdot}79)^3.\,\frac{s^8}{[s^2+6{\cdot}79^2]^5\,[s^2+4{\cdot}79^2]^5}. \quad (22b)$$

Values of σ_c for Fe^{+16} and Fe^{+15} different values of '*s*' are given in Table 7.

Electron Balance of the Fe-*ions on passage through the Solar envelope.*

From the above results on the loss and capture cross-sections of highly ionised atom-ions, we can visualise to some extent the problem of their electron-balance, as they pass through the solar envelope. We assume that the Fe^{+16}-ion is formed with an energy of 60 mev., $V=6{\cdot}5$ *cf.* According to (17), the Fe^{+16} can never lose any further electron as this velocity is < 8·06 which is the critical value of *s* for this ion (*vide* Table 6).

[2] This formula is different from K. and B.'s No. (4), by the factor $\frac{2^3}{z'^3}$. As K. and B. treat a case where $z'=2$, their calculations remain unchanged.

But the Fe^{+16}-ion can capture an electron, for at this velocity we find from Table 7 that $\sigma_c \simeq 1{\cdot}4\times10^{-20}$ cm.[2] and the value increases as the velocity falls. The capture takes place after the Fe^{+16}-ion has traversed approximately 7×10^{19} H-atoms, or even less. By this time we calculate from (3*a*) that the energy falls to $\simeq$58 mev. and the velocity to $s=6{\cdot}4$.

Career of the Fe^{+15}*-ion.*

For the Fe^{+15}-ion, the critical velocity for loss is $s=5{\cdot}01$ *cf.* But the Fe^{+15}-ion may start with a velocity of 6·4 *cf* and σ_l at this point$=1{\cdot}3\times10^{-18}$ cm^2. This is a rather large value, and Fe^{+15} has a chance of losing the electron as soon as it is captured. This may happen, but all this while, the ion goes on losing energy, and the process is repeated, but with lesser chances for loss and increasing chances of capture. So during the stretch $s=6{\cdot}4$ to $s=5{\cdot}01$, Fe^{+15} may lose and capture electrons a large number of times till ultimately at $s=5{\cdot}01$ corresponding to the energy 35·55 mev. σ_l vanishes altogether. The ion, by now, has traversed nearly 4×10^{20} H-atoms (*vide* Fig. 1). There are still about 7×10^{20} H-atoms to traverse.

The Fe^{+14} *ion.*

From $s=5{\cdot}01$ to 4·84, $E=35{\cdot}55$ mev. to 33·22 mev. the Fe^{+14}-ion will have a career similar to that of the Fe^{+15}-ion. The loss cross-section for Fe^{+14} at $s=5{\cdot}01$ amounts to $1{\cdot}37\times10^{-19}$ cm^2. The capture cross-section cannot be estimated as the capture is now in the 3*p*-orbit. Let us suppose that it is 1/10 that for the 3*s*-orbit for a similar ion, with $s=5{\cdot}01$. Then we have $\sigma_c\simeq5\times10^{-21}$ cm.[2] and this varies rather gently with velocity. So at first Fe^{+14}-ion will lose electrons more frequently than it captures but as the velocity falls to $s=4{\cdot}84$, σ_l vanishes and Fe^{+14} can only capture an electron, and be converted to Fe^{+13} either in the $3p\;^2P_{\frac{1}{2}}$ or in the $3p\;^2P_{\frac{3}{2}}$-state. But on account of the smaller value of σ_c, viz. 5×10^{-21} cm.^{2} the Fe^{+13}-ions have a chance of reaching greater heights, i.e. even a region where H-atoms do not exist, with small velocities. If the capture is in the $3p\;^2P_{\frac{3}{2}}$-orbit, conditions are favourable

TABLE 7.

σ_c-*Values.*

log (σ_c/a_B^2) \ *s*	8	7	6	5	4	3	2	1
Fe^{+16} ..	$\bar{4}$·3214	$\bar{4}$·5694	$\bar{4}$·7632	$\bar{4}$·8636	$\bar{4}$·8024	$\bar{4}$·4584	$\bar{5}$·5921	$\bar{7}$·5491
Fe^{+15} ..	$\bar{4}$·3803	$\bar{4}$·6453	$\bar{4}$·8621	$\bar{4}$·9890	$\bar{4}$·9593	$\bar{4}$·6483	$\bar{5}$·8160	$\bar{7}$·7990

for a forbidden transition to $3p\ ^2P_{\frac{1}{2}}$, for the time of flight is nearly 10 seconds, and there are very few electrons or atoms to encounter. Following the general procedure laid down by Condon and Shortley, Pasternack (1940) has calculated the values of transition probabilities of the metastable levels arising from p^x-combinations ($x=1$ to 5). From the values of these transition probabilities and the intensity of the coronal lines, it will be possible to calculate the number of Fe^{+}-ions streaming through the solar envelope, and thus forming an estimate of the contribution of this process to the total energy production in the sun. But these considerations are postponed pending calculations of the capture cross-sections in the $3p$-orbits.

The formation of the other iron-ions with lower net charge, viz. of $Fe^{+12}\ 3p^2$, $Fe^{+11}\ 3p^3$, $Fe^{+10}\ 3p^4$, $Fe^{+9}\ 3p^5$. . . . . . takes place according to the same process as is described for Fe^{+13}, by successive capture of electrons, after the velocity of the ion has been reduced by the ionisation-loss to the critical values. A detailed discussion is postponed pending the calculation of p-capture cross-sections.

From this dicussion, it appears that Fe^{+13}-ion will be formed usually at a lower level than the succeeding ions, and the Fe^{+9}-ion will be formed at the highest level. But these formation processes all take place in the highest level chromosphere, and the technique is probably not sufficiently advanced to enable astrophysicists to find out the levels where these lines originate.

Conclusion

If the considerations presented in this paper be correct, the occurrence of the coronium lines in the solar corona form the first clear fingerpost that nuclear reactions are not confined to the interior of the stars, as already postulated with a certain amount of success by Gamow (1939), and Bethe (1938), and others, but they also take place on the surface of the Sun, and therefore generally on stars as well, and modify in varying degrees the phenomena taking place there. In this connection, the following intuitive remarks of the late Lord Rutherford may be quoted:

'In the furnace of the Sun and other hot stars, the electrons, protons, neutrons, and atoms present must be endowed with high average velocities owing to thermal agitation. It is thus to be expected that the processes both of disintegration and aggregation of nuclei, such as are observed in the laboratory, should be operative on a vast scale for all nuclei, and that a kind of equilibrium should be set up between these two opposing agencies of dissociation and association for each type of atomic nucleus.'

But it is obvious that before we can go to the root of the problems raised by the extraordinary discovery of the origin of coronal lines by Grotrian and Edlen, a large amount of theoretical work and practical observations and work are needed. As the writer of the present paper will not be in a position to tackle all these problems single-handed, or resume these studies for some time, a brief résumé of some of these problems is given:—

(1) The production of stripped iron and other atoms has been supposed to be due to some kind of nuclear reaction, analogous to Uranium Fission, but the heaviest elements so far discovered on the Sun are Ra^{226} (this is considered doubtful by some). Osmium and Platinum, Uranium and Thorium lines have not so far been discovered, probably because the spectra of these elements have not been so far analysed and classified. It will be a useful task to get the lines of the fission elements classified and look for their occurrence in the Sun.

With respect to the probability of threefold or fourfold fission, fresh experiments are obvious suggestions; if the Fe and Ni-ions responsible for the coronium lines consist of the usual isotopes they should be the end-products of a successive series of α-ray disintegrations, and hence the primary product of fission may be some element with a lesser charge, say $_{23}V^{60}$ or $_{24}Cr^{50}$ but with an extraordinarily large mass, far larger than that of the isotopes of these elements occurring in Nature. This may occur from the fission of the A-products or B-products (Saha, 1941), some of which have very large mass and may therefore possess an inherent instability for fission.

This subject belongs obviously to nuclear physics and has been treated in detail by Bohr and Wheeler (1939), and Flügge (1939).

(2) We require a better knowledge of the composition and density-gradient of the elements in the reversing layer, the chromosphere, and the corona. Our knowledge of the transition layer between the top of the chromosphere (14″) and the beginning of the inner corona (48″) is particularly defective. Very good work on this line can be done during total solar eclipses, when attempts should be made to photograph fainter coronal lines and prove or disprove their presence. The transitional region may be investigated by means of a powerful Lyot coronagraph at good heights, say at Kodaikanal.

(3) Some progress has been made on the explanation of the peculiarities of the inner and the outer corona on the basis of the δ-ray theory, briefly referred to in § 3, but the matter is so extensive that it can be taken up only in a separate article.

The author expects to return to these and other problems which obviously suggest themselves to an astrophysicist, as soon as circumstances allow him to do so.

It is a great pleasure to record my thanks to my pupils who have taken part in the discussions and helped in the calculations. Mr. D. Kundu has gone through the spectroscopic data as far as available; Messrs. P. C. Bhattacharyya and S. K. Ghosh have checked the calculations and helped in drawing the figures.

REFERENCES.

ANDERSON, 1926, *Zs. f. Physik*, **37**, 342 (previous references will be found there).
BABCOCK, 1934, *Proc. Ast. Soc. Pac.*, **46**, 132.
BETHE, 1932, *Zs. f. Physik*, **76**, 293.
1938, *Phys. Rev.*, **54**, 436.
BHATTACHARYYA, P. C., 1941, *Proc. Nat. Inst. Sci.*, **7**, 275.
BLOCH, 1933, *Ann. d. Physik*, **16**, 285.
BOHR AND WHEELER, 1939, *Phys. Rev.*, **56**, 426.
BOHR, 1940, *Phys. Rev.*, **58**, 650.
1941, *Phys. Rev.*, **59**, 270.
BOWEN, 1936, *Rev. Mod. Phys.*, **8**, 55.
BOWEN AND WYSE, 1940, *Lick Obs. Bull.*, **19**, 1.
BUMBAUCH, 1937, *A. N.*, 263.
CILLIÉ AND MENZEL, 1935, *Harvard Circular*, 410.
CONDON AND SHORTLEY, *The Theory of Atomic Spectra.*
FLÜGGE, 1939, *Zs. f. Phys. Chemie*, B, **42**, 274.
GAMOW, 1939, *Phys. Rev.*, **55**, 718.
GROTRIAN, 1931(*a*), *Zs. f. Ast. Physik*, **2**, 106.
1931(*b*), *Zs. f. Ast. Physik*, **3**, 199.
1933, *Zs. f. Ast. Physik*, **7**, 26.
1934, *Zs. f. Ast. Physik*, **8**, 124.
HENDERSON, 1923, *P.R.S.L.* (A), **102**, 496.
HEISENBERG AND EULER, 1934, *Naturwissenschaften.*
JACOBSEN, 1930, *Phil. Mag.*, **10**, 401.
KNIPP AND TELLER, 1941, *Phys. Rev.*, **59**, 659.
KRAMERS AND BRINKMANN, 1930, *Proc. K. A. Amsterdam*, **30**, 973.
KUNDU, 1942, *Science and Culture*, **7**, 364.
LAMB JR., 1941, *Phys. Rev.*, **58**, 696.
LEHMANN, 1927, *P.R.S.L.* (A), **115**, 624.
LIVINGSTONE AND BETHE, 1937, *Rev. Mod. Phys.*, **9.**
LYOT, 1934, *Zs. f. Ast. Physik*, **5**, 73.
1936, *M.N.R.A.S.*, **99**, 580.
1937, *L'Astronomie*, **51**, 203.
MCCREA, 1929, *M.N.R.A.S.*, **89**, 483.
1934, *M.N.R.A.S.*, **95**, 80.
MENZEL, 1931, *Lick Observatory Bull.*, **17**, 348.
MILLMANN, 1933, *Pop. Astr.*, **41**, 298.
MILNE, 1921, *M.N.R.A.S.*, **81**, 375 and onwards.
MINNAERT, 1930, *Zs. f. Ast. Physik*, **1**, 226.
MITCHELL AND E. T. R. WILLIAMS, 1933, *Astro. Jour.*, **77**, 197.
MOORE, 1934, *Proc. Ast. Soc. Pac.*, **46**, 298.
NAGARAJA AIYYAR, PRINGSHEIM, *Physik der Sonne.*
PANNEKOCK AND MINNAERT, 1928, *Verh. Akad. Wet. Amsterdam*, **13.**
PASTERNACK, 1940, *Ast. Phy. Jour.*, **92**, 129.
PEREPELKIN AND MELNIKOV, 1935, *Pulkovo Bulletin*, No. 122, 14.
ROSSELAND, 1933, *Pub. Obs. Univ. Oslo*, No. 5.
1934, *Theoretical Astrophysics*, Chap. XIV.
RUSSELL, 1929, *Astrph. Jour.*, **69**, 49.
1929, *Astrph. Jour.*, **70**, 11.
1941, *Scien. American*, August.
Saha, 1941, *Science and Culture*, **7.**
STOBBE, 1930, *Ann. d. Physik*, **7**, 661.
THACKERY, 1941, *Report on Solar Physics* (Progress of Physics, Physical Society, London). **7**, 160.
THOMPSON, J. J., 1932, *Conduction of Electricity through Gases*, p. 97.
Unsöld, *Physik der Sternatmosphäre*, Kap., **17.**
WALDEMEIER, 1938, *Zs. f. Ast. Physik*, **15**, 44.
WILLIAMS, 1932, *P.R.S.L.*, (A), **135**, 108.

74. CAPTURE OF ELECTRONS BY POSITIVE IONS WHILE PASSING THROUGH GASES

M. N. SAHA* AND D. BASU

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This work extends that of Brinkman and Kramers on the capture of electrons by positive ions while passing through gases. Detailed mathematical working is reported, and it is shown that contrary to the opinion of Brinkman and Kramers, the probability of capture of an electron by the α-particle in the $2p$-orbit from the H-atom becomes much larger than that for the capture in the $1s$-orbit when the velocity falls below $2\ (2\pi e^2)/h$. For small velocities, the ratio goes on increasing.

An α-particle passing through a gaseous medium as in a cloud chamber produces a track consisting of ions formed round electrons liberated from the surrounding gas. It was noticed by Henderson (1923) and Rutherford (1930) that towards the end of the track the phenomenon was more complex. They found that when the velocity had slowed down to a value comparable to $2c_\alpha$(c_α=the velocity of the outer electron in the normal level of the H-atom in the molecules of the gas through which the α-ray passes) the α-particle might capture an electron and be converted to He^+, this might again lose its electron on collision with matter. The phenomenon of alternate loss and capture may occur a large number of times, but ultimately when the particles have sufficiently slowed down, most of them would permanently acquire an electron and be He^+. As He^+ further passes through the gas, it may capture an electron and become neutral helium. As it has a velocity of the order of 10^7 to 10^8 cm sec.$^{-1}$ it may again lose an electron by collision with matter. This process of alternate loss and capture may continue for some more distance till the velocity slows down sufficiently and ultimately we get neutral helium atoms.

*Fellow of the Indian Physical Society.