which, except at the magnetic equator, and at the magnetic poles, cannot be linked to the local coordinates in a simple manner.

At the magnetic equator, the X and Y axes are horizontal and Z-axis is vertical. In a vertical propagation of the e.m. wave $E_z=O$, and we have only E_x and E_y definite. The reflected wave will therefore have its o-component polarized parallel to the magnetic field, the X-component polarized parallel to the Y-axis, *i.e.*, perpendicular to the magnetic field in a horizontal direction. We have, however, not yet tried to evaluate E_x, E_y in terms of the amplitudes of the wave sent out by the antenna.

For the magnetic pole, the X-axis is vertical, and for a vertical propagation we have $E_x=O$, and we have only $E_y \pm i_z E$, *i.e*, two circularly polarized X-waves. We have to obtain the reflexion coefficient from a solution of (21), which will be attempted in a future paper.

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76. A PHYSICAL THEORY OF THE SOLAR CORONA*

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§ 1. Introduction

Nearly twenty-five years ago, when the present writer was preparing his paper "On a physical theory of stellar spectra" (Saha, 1921), he had the benefit of very sound advice from the late Professor Alfred Fowler, who allowed him to make free use of his (Fowler's) own unrivalled knowledge of spectroscopy and of stellar spectra. Fowler's remarks on this theory, which to my knowledge were never put in print, may now be disclosed. "The thermal ionization theory", he told me repeatedly, "accounts in a general way for the spectra of normal stars; but there are very important exceptions, e.g. the stars with peculiar spectra, the planetary nebulae; even in the case of normal stars, the great strength of Balmer lines of hydrogen which persists throughout all stellar classes is a disquieting feature, and in the case of the sun, the peculiar behaviour of helium cannot, in my opinion, be accounted for by the thermal ionization theory at all".

During the past twenty-five years, many of these points raised by Fowler have been taken up by well-known workers: Darwin, R. H. Fowler and Milne, Zanstra, and others in this country, mostly on the theoretical side; and by Russell, Bowen, Struve, Menzel, Payne, and their co-workers in the U.S.A., Unsöld, Pannekoek, and other workers on the Continent. But the helium problem appears to have remained very much as it was twenty-five years ago. Briefly the problem is as follows: The Fraunhofer spectrum of the sun shows only the lines of such elements as have excitation potentials (energy values of the lower state) between zero and 10 volts; in the chromospheric spectrum, the lines of ionized elements are relatively stronger but in no case, helium excepted, do we get lines of stronger excitation than 14 to 15 volts (energy value of upper state). The lines of He do not occur at all in the normal Fraunhofer spectrum, except over disturbed regions, like penumbra of sunspots, but occur prominently in the flash spectrum up to heights of 7500 km. These lines have an excitation poetntial exceeding 20 volts; but the line of ionized helium $\lambda 4686$, $\nu = 4R\left(\frac{1}{3^2}-\frac{1}{4^2}\right)$ occurs as a prominent but low-level chromospheric line scarcely exceeding 2000 km. in height. This line has an excitation potential of about 75 volts, and one fails to see how such high excitation can exist in the sun, and that too in the lower levels.

The points were repeatedly urged by Professor A. Fowler, and were repeated by myself later on many occasions and have also received attention from others.

*For fuller details, see Saha (1942).

There are certain additional features regarding the occurrence of He lines. I think it was Evershed who first drew attention to the fact that the chromospheric He lines tend to get fainter and ultimately disappear towards the limb. The matter was confirmed by Pannekoek, and Minnaert (1928), and more fully by Perepelkin and Melnikov (1935). The findings of the later workers are represented in table 1 and figure 1, taken from their works.

TABLE 1

Height (km.)	E (erg/cm.^{3} sec.)	Height (km.)	E (erg/cm.^{3} sec.)
500	39×10^{-6}	4000	60×10^{-6}
1000	125	4500	29
1500	186	5000	12
2000	212	5500	4·3
2500	195	6000	1·3
3000	151	6500	0·3
3500	100	7000	0·1

These results are inexplicable on the ionization theory, or any modification of it. For some time past I have been thinking of another explanation, which I hesitated to put forward on account of its radically heterodox nature. Allowing that He exists in some quantity in the solar atmosphere, it is clear that neither the ultra-violet radiation from the sun nor the thermal conditions existing on the

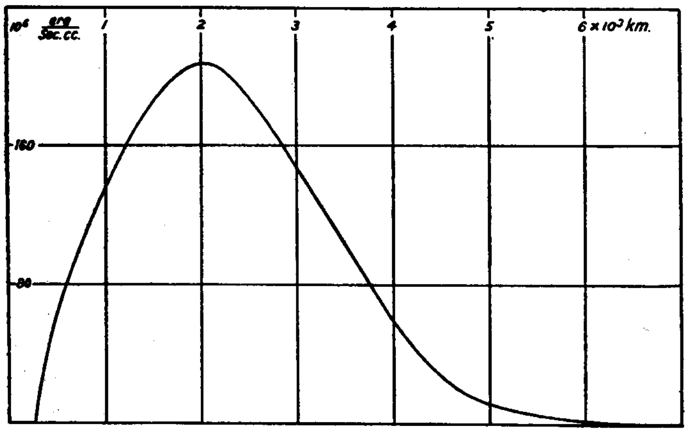

Fig. 1

surface of the photosphere is capable of exciting it to luminescence in the way we obtain in the sun. The suggestion regarding their origin is as follows:—First, suppose that α-particles are constantly being produced throughout the solar surface, as a result of some nuclear reaction, and hurled forth through the solar atmosphere. As they pass through the solar gases (mostly hydrogen), they go on ionizing these atoms by collision (as in J. J. Thomson's theory of ionization by collision), and continuously losing energy. When their energy has sufficiently diminished, they capture an electron in any orbit and become normal or excited He^+. The excited He^+ atom may radiate energy of which only λ4686, and possibly the lines $\nu=4R\left(\frac{1}{4^2}-\frac{1}{m^2}\right)$, are within observable range. The He^+ atom moves forward along the original direction but it goes on losing energy, which is spent, as in the case of He^{++}, in releasing electrons from atoms by collision. When its velocity of motion has sufficiently diminished, it may capture a second electron, and become a normal or excited He atom. The excited He atom gives us the high-level chromospheric He lines.

This phenomenon of capture of electrons by α-particles to form He^+ and He was discovered by Rutherford and Henderson (1923) while studying α-tracks in the cloud-chamber. The capture of the first electron begins to take place when the velocity of the α-particle has fallen to $2c\alpha$, where c is the velocity of light and α the Sommerfeld constant. It may be recalled that $c\alpha$ is the velocity of the electron moving in the first orbit of the H atom. We have $c\alpha=2{\cdot}18\times10^5$km./sec. We shall have frequently to express velocities in this paper in terms of $c\alpha$ as unit in the form $V=sc\alpha$, where s is a numerical coefficient. In the cloud-chamber, when the α-particle starts to move, it does so with a velocity of the order of $9c\alpha$ (for α-particles of range 11 cm. from Th C″). It goes on producing electrons by collision, and thus gradually loses energy. When the last centimetre is reached, and its velocity has reached $2c\alpha$, corresponding to an energy of 1×10^5 volts, and range of about 0·46 cm., the α-particle begins to capture electrons to an appreciable degree.

But He^+ which is formed by the capture of an electron may again lose this electron by collision with atoms, and again become He^{++} or α-particle. In fact Rutherford (1924) showed that this alternate loss and capture of electrons may occur thousands of times within the last millimetre of the range of the α-particle, but all the time the velocity of the α-particle or of He^+ is falling, and when it reaches $\simeq c\alpha$, He^+ may capture a second electron from cloud-chamber gases and become He. But this may be again ionized to He^+, until ultimately we get He, and the track terminates.

A mathematical theory of this effect has been worked out by Oppenheimer (1928) and by Kramers and Brinkmann (1930), and applied by Jacobsen (1935) for explaining the velocity-range phenomenon in the experiments of Rutherford and Henderson, and also in his own experiments.

The suggestion regarding the occurrence of He^+ and He lines is equivalent to saying that the cloud-chamber phenomena described here occur on the sun on a gigantic scale, but the α-particles are due not to natural radioactive bodies but to some reaction taking place on the solar surface. In the cloud-chamber, some of the α-particles must be capturing electrons in excited orbits, but we cannot observe emission of the characteristic lines of He, owing to their feebleness. The same is true of the capture of electrons from atoms by He^+. But in the sun the captures are sufficiently numerous and the lines emitted are strong enough to be observed in the flash. The explanation accounts in a satisfactory manner, at least qualitatively, for the occurrence of λ4686 in some strength in the lower chromosphere (up to a height of 2000 km.), and of the occurrence of He lines in the higher chromosphere up to heights of 7500 km., and also their tendency to disappear towards the limb.

There is only one apparent difficulty in this hypothesis of the origin of He^+ and He lines on the sun. According to laboratory observations so far available, the capture of the electron by He^{++} begins to take place when $V \simeq 2c\alpha$, and of the second electron by He^+ when $V \simeq c\alpha$. The He atoms in the sun ought therefore to be in motion with velocities of this order. But this is not apparently observed, though the He lines are actually found broad. The explanation is probably to be found in the fact that α-particles originate below the reversing layer, and by the time they come out of this region they have dissipated most of their energy in the process of ionizing other particles by collision.

If these suggestions stand criticism, it should be possible for us to calculate the intensity of ultra-violet emission from the sun due to He^+ and He, and estimate their relative importance in promoting ionization of the earth's upper atmosphere.

Alpha-particles are produced in many nuclear reactions, and at this stage it is needless to look for any particular reaction which may be mainly responsible for its production on the solar surface. The question is whether α-particles on such vast scales can be produced on the surface of the sun. If so, what is the subsequent fate of these particles ? Do they sink deep, get doubly ionized in the interior, and contribute to restoring the α-particle balance of the interior of the sun ? These questions may stand for the moment.

It is also worthy of notice that though the visible lines of He are not usually found in the Fraunhofer spectrum, Babcock (1934) records λ10830, which is $1s2s\ ^3S - 1s2p\ ^3P$ as a faint absorption line in the infra-red part of the Fraunhofer spectrum. This line requires for its production as absorption line some accumulation of He in the $1s2s$ state, which is metastable. This indicates that He exists in some strength in the reversing layer in the normal $1s^2$ and $1s2s$ states, but not in the $1s2p$ or any higher state. The finding is not, in my opinion, antagonistic to the hypothesis of formation of He in the solar atmosphere out of α-particles.

It is obvious that the hydrogen atmosphere of the sun may also originate, at least partly, in the same way, for the proton is also a most frequent product of nuclear reactions. But a hydrogen atom once formed by the capture of an electron by the proton in the first or, better, in the second orbit can be sustained by radiation pressure, so its career should be fundamentally different from that of the He atom.

It is the belief of the present author that many outstanding problems of the solar and stellar atmospheres, such as prominences, spots, flares giving rise to radio fade-outs, may find their explanation in nuclear reactions taking place more vigorously on limited parts of the surface. It is quite probable that nuclear reactions of the type considered take place more vigorously in the interior, as shown by Bethe (1939) and Gamow (1939), but the probability of their occurrence on the surface on a reduced scale cannot be excluded. For example, it has been found that the He line λ5876 occurs as an absorption line in the neighbourhood of disturbed areas, namely, penumbrae of spots. Probably nuclear reactions producing particles are the cause of formation of such disturbed regions, and reactions are much more vigorous than on the normal surface, and a temporary He atmosphere sufficient to give us D_3 in absorption may be formed in these regions.

§2. The Problem of the Solar Corona

Extraordinary interest, in spite of the war, has been aroused in recent years in the problems of the outermost part of the solar atmosphere (inner and outer corona) by the work of Edlén (1942) on the identification of coronium lines. The story of this identification has been told by Russell (1941), by Swings (1943), and by Edlén himself in an exhaustive memoir (1942), and need not be repeated here. It appears to have been conclusively proved that most of the coronal lines are due to atoms of Fe, Ni and Ca which have lost a large number of their outer electrons, sometimes amounting to as many as fifteen or sixteen. The details of this identification, as far as required for our purpose, are given in table 2.

As there appears to be no way of denying the accuracy of the identification, the astrophysicist is faced with a number of problems of a unique type, which may be enumerated as follows:

(1) What is the physical process giving rise to such highly charged ions ?

(2) How can these highly charged ions, once produced, maintain their charge in the solar atmosphere ?

(3) To explain the other characteristics of these lines noted by Lyot (1939) and in the eclipse expeditions, namely, the great breadth of these lines towards their base, sometimes amounting to 1A., which gradually diminishes outwards, the intensity variations of these lines, etc., along with phases of solar activity.

These may be called "Coronium problems", in contrast to the second set of problems now to be discussed which

Table 2*

Wave-length (A)	Intensity		Identification		Ionization potential (ev.)
	Grotrian	Lyot	Ion	Transition	
3328·1	1·0		Ca XII	$^2P_{3/2}$–$^2P_{1/2}$	589
3388·10	16		Fe XIII	$^3P_2$–$^1D_2$	325
3454·13	2·3				
3600·97	2·1		Ni XVI	$^2P_{1/2}$–$^2P_{3/2}$	455
3642·87			Ni XIII	$^3P_1$–$^1D_2$	350
3800·77					
3986·88	0·7		Fe XI	$^3P_1$–$^1D_2$	261
4086·29	1·0		Ca XIII	$^3P_2$–$^3P_1$	655
4231·4	2·6		Ni XII	$^2P_{3/2}$–$^2P_{1/2}$	318
4311·5					
4359					
4567	1·1				
5116·03	4·3	2·6	Ni XIII	$^3P_2$–$^3P_1$	350
5302·86	100	120	Fe XIV	$^2P_{1/2}$–$^2P_{3/2}$	355
5694·42		1·5			
6374·51	8·1	28	Fe X	$^2P_{3/2}$–$^2P_{1/2}$	233
6701·83	5·4	3·3	Ni XV	$^3P_0$–$^3P_1$	422
7059·62		4			
7891·94		29	Fe XI	$^3P_2$–$^3P_1$	261
8024·21		1·3	Ni XV	$^3P_1$–$^3P_2$	422
10746·80		240	Fe XIII	$^3P_0$–$^3P_1$	325
10797·95		150	Fe XIII	$^3P_1$–$^3P_2$	325

*Taken from an article by Swings (1943).

TABLE 3

*Electron density at various heights in the corona**

h (minutes of arc)	N	h (minutes of arc)	N
0·00	$4·58\times10^8$	22·4	$1·79\times10^6$
0·48	3·11	25·6	1·35
0·96	2·29	28·8	1·10
1·6	1·56	32·0	$9·13\times10^5$
3·2	$7·04\times10^7$	40·0	6·32
4·8	3·84	48·0	5·12
6·4	2·38	64·0	3·81
9·6	1·11	80·0	2·49
12·8	$6·13\times10^6$	112·0	1·63
16·0	3·73	144·0	1·10
19·2	2·50		

*Taken from Unsöld's *Sternatmosphäre*, 1939, chap. 17.

may be called the "Corona problems". The two sets of problems must be discussed together as they are complementary. The coronium lines are found to occur in the "Inner corona"—which extends from beyond the top of the chromosphere (height, 14,000 km.), sometimes to a distance of about 10′ ($4·4\times10^5$ km.) from the photosphere. The inner corona shows, besides the coronium lines a continuous spectrum, which, though nearly a million times fainter, is of the same type as the photospheric spectrum, but with the Fraunhofer lines blurred out. In the outer corona, however, the coronium lines disappear, but the Fraunhofer lines reappear in its continuous spectrum.

The continuous spectrum of the corona has received attention from a number of workers, namely, Minnaert (1930), Grotrian (1933, 1934), and several others. They have proved that it is due to the Rayleigh scattering of photospheric light by an atmosphere of electrons as suggested by Schwarzschild nearly thirty years ago. From the variation of intensity of the coronal light with distance from the photosphere, it is possible to estimate the electron density at different heights, and the figures for a mean corona are reproduced in table 3.

The great difficulty has been to find the source of the electrons constituting the corona. They cannot arise from thermal or photoelectric ionization of solar atoms, as we have then to postulate in coronal heights the existence of a comparable concentration of atoms and ions, which is impossible on dynamical grounds. The best hypothesis appears to be that of Minnaert (1930), and may be given in his own words: "Anderson (1926) 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 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 being projected towards space."

According to Grotrian (1934), the continuous spectrum of the scattered radiation from the *inner corona* shows depressions in regions corresponding to chief Fraunhofer absorption lines, but amounting in width to about 100A., but the lines reappear in the outer corona. He sought to explain the first observation by the hypothesis that the electrons in the inner corona are moving outwards with velocities of the order of 4000 km./sec. According to Moore (1934), the velocity of the coronal streamers (electrons) amounts to 20 to 30 km./sec. These figures probably refer to the outer corona.

Many investigators, including Edlén himself, have sought to explain the occurrence of coronium lines on a temperature basis. The arguments are two-fold:

(1) The coronal lines are, according to measurements of Lyot, quite broad, of the order of 1A., and if the width be due to Maxwellian motion of the emitting particles, the temperature ought to be $2·34\times10^6$°C. This temperature is sufficient to produce the required amount of ionization of the Fe and other atoms.

It is, however, difficult to think of any physical mechanism by which such high temperatures can be produced all over the outer layers of the sun. "Temperature" always means some equilibrium condition, and possibly a small blackbody, placed at the coronal heights, would not show a higher temperature than 3000 to 4000°C. We may, however, have high local temperatures over limited regions, as in the case of a rocket burst in our own atmosphere, where we may have a small region around the rocket in which very high temperatures prevail for a short period of time. Several workers have hinted that the production of highly stripped iron, nickel and calcium ions responsible for the emission of coronium lines may be due to the bombardment of the solar atmosphere by meteoric matter in the way imagined by Lindemann and Dobson for explaining meteoric flashes in the earth's atmosphere. But the essence of the Lindemann-Dobson theory is that the meteor, striking the earth's atmosphere with a velocity ranging between 7 and 26 km., drives before it the whole column of air in its path, which is heated by adiabatic compression to a temperature sufficient to bring meteoric matter to luminescence. Lindemann and Dobson found that the gas pressure at the heights where the meteor strikes should be far larger than could be concluded from meteorological considerations. In the sun, the meteoric matter would fall with a velocity of 622 km./sec., but would probaly get vaporized long before it reached the chromosphere, and even if some fragments escaped vaporization, the amount of matter in its path would be far too small for production of high temperatures according to the Lindemann-Dobson process. For the meteoric matter which vaporized, the atoms would be rushing with velocities of the order of 622 km./sec. into the solar atmosphere. The effect on these atoms may be obtained by supposing them to remain at rest, and allowing the solar

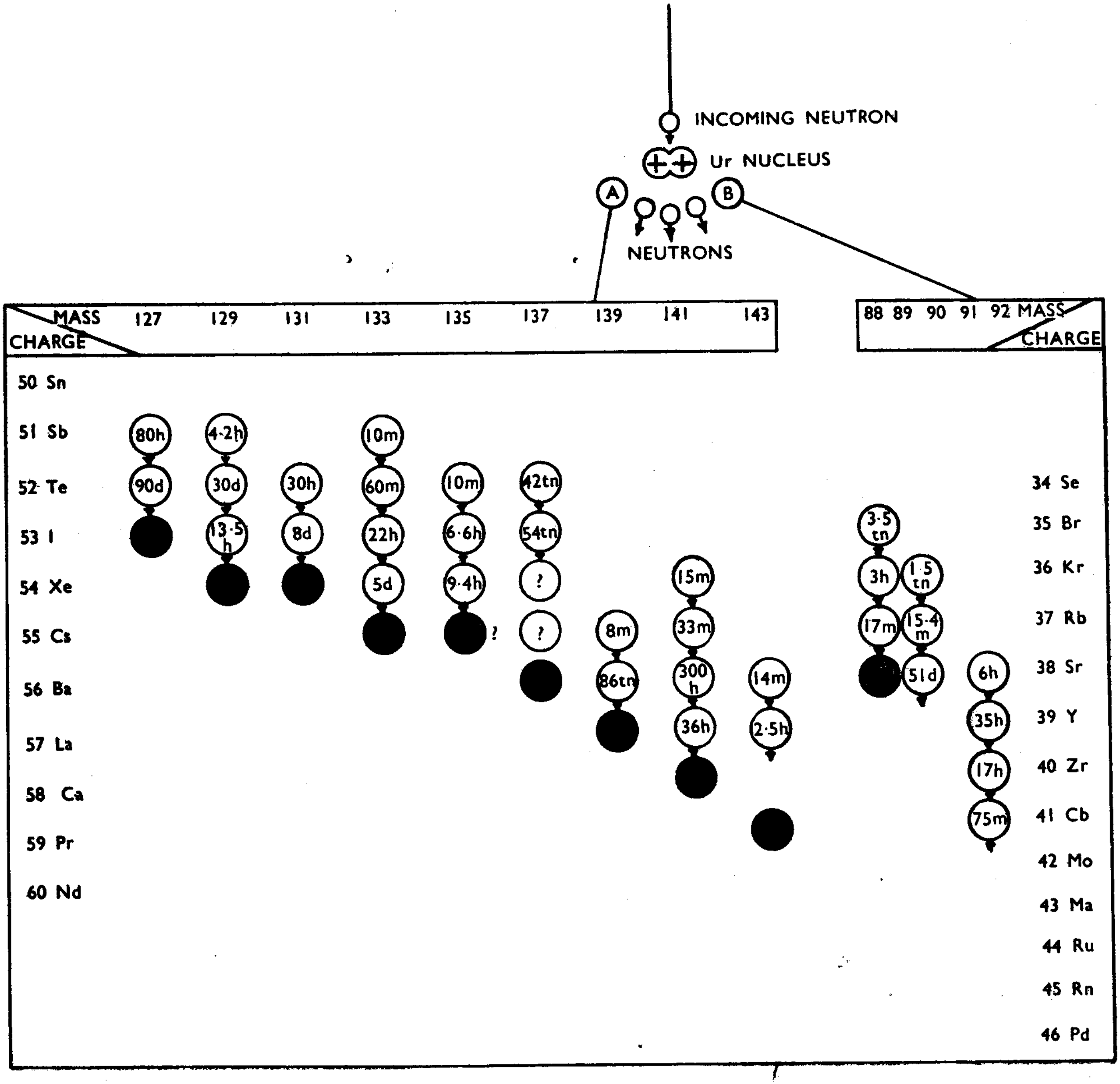

Figure 2.

atoms to rush past them with velocities of the order of 622 km./sec. As far as free and bound electrons are concerned, this is equivalent to bombarding the atoms with electrons having an energy of $\simeq 10$ volts, which is not sufficient even to tear the outermost electrons from the meteoric atom. As far as the nuclei of solar atoms are concerned, we need take only H nuclei. Their energy is of the order of 5000 volts, and such particles can tear out only one or two outer electrons at each encounter. The meteoric atoms can be deprived of 10 to 14 electrons only when they plunge very deep into the sun, but not at coronal heights. Further, Waldmeier (1938) has shown that the contour of the width curve of the coronal lines as found by Lyot can also be explained on the supposition that the emitters of coronal lines are streaming outwards or inwards with a velocity of 60 km./sec. Lyot (1934) 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 Waldmeier's suggestion, shows that the emitters of coronal lines are streaming out of the sun with velocities which go on diminishing as greater heights are reached. The meteoric flash theory is not therefore sufficient to explain either the high ionization or the increasing width of coronal lines towards the solar limb, as actually found by Lyot and Waldmeier (1944).

The writer (Saha, 1942) has ventured to suggest that the Fe and other ions responsible for the emission of the coronium lines are due to some nuclear process identical, with or akin to that of nuclear fission, discovered by Hahn and Strassemann in 1939. The story of this discovery may be read in several excellent reports on the subject (Livingston, 1941; Walke, 1941), but the facts necessary for astrophysical purpose may be briefly described. It was found by Hahn and Strassemann that when heavy nuclei like ^{238}U, ^{235}U, ^{232}Th, ^{229}Pa are bombarded by neutrons, fast or slow, they break up according to the scheme (for ^{235}U) (figure 2):

$$^{235}_{92}U+{}^{1}_{0}n={}^{M_1}_{x}A+{}^{M_2}_{y}B+Z\,{}^{1}_{0}n+Q.$$

${}^{M_1}_{x}A+{}^{M_2}_{y}B$ are nuclei having respectively the charge numbers x and y, and mass-numbers M_1, M_2; Z is the number of neutrons, generally 3 or 4, which evaporate in the process (Szilard and Zinn, 1942); Q is the energy evolved in the process.

$$x+y=92,\quad M_1+M_2=236-Z.$$

The A products have been found to have x varying from 46 to 60, the B products have y varying from 35 to 46. The reaction is exothermic, as can be seen from mass relationships, and Q is $\simeq 200$ mev. for binary fission, and it is distributed, according to the law of conservation of energy and momentum, between A and B, A receiving $QM_2/(M_1+M_2)=Q_A$ and B receiving $QM_1/(M_1+M_2)=Q_B$, respectively.

Neither the A nor the B products are stable on account of the high proportion of neutrons, but each has to emit 3 or 4 β-rays successively, till they are reduced to stable forms, as might be illustrated in the chain processes

A $M=141$	Xe→ 54	β Cs→ 55	β Ba→ 56	β La→ 57	β Ce (stable) 58
		15^m	33^m	300^h	36^h
B $M=91$	Sr→ 38	β Y→ 39	β Zr→ 40	β Nb→ 41	β Mo (stable) 42
		8^h	38^m	17^h	75^m

The fission process is beautifully illustrated in the Wilson-chamber photographs taken by Corson and Thornton (1939), Böggild *et al.* (1941) in Prof. Bohr's laboratory before Denmark was invaded.

What is important for our purpose is the high energy with which the fission fragments are thrown out in the reaction. To take an example: If $x=54$, $M_1=141$, $y=38$, $M_2=91$, $Z=4$, we have $Q_A \simeq 80$ mev. and $Q_B \simeq 120$ mev. The velocities corresponding to these energies are $V_A \simeq 4{\cdot}7\, c\alpha$, $V_B \simeq 7{\cdot}1\, c\alpha$. These velocities are much larger than the orbital velocity not only of the outer electrons of the stable products, but also of many of their inner electrons. Bohr (1941), Knipps and Teller (1941) and Lamb (1941) have pointed out that as soon as the fission fragments are produced in any medium, they lose most of their outer electrons and can retain only those of their inner electrons whose orbital velocities are larger than, or comparable to, their own velocity. The fission particles therefore start as heavily ionized ones bereft of a large number of their outer electrons, and Bohr and Wheeler (1939) quote a Russian worker, Perlov (?), as having experimentally proved that the charge may be as high as 20.

The presence of Fe or Ni amongst the fission fragments has not yet been reported with definiteness, but considerations of energy and probability do not rule them out. Nishina and his co-workers (1939) have shown that the probability of a symmetric fission in which one fragment is much larger than the other increases with the energy of the bombarding neutrons. Further, ternary and quaternary fission are allowed by considerations of energy and probability, and Q in some cases may be as high as 250 mev., which is larger than the 200 mev. maximum energy evolved in the binary fission process. It may be supposed that as a result of either of such processes taking place in the sun, smaller fragments are produced which, after a number of β-emissions, ultimately stabilize as nuclei of elements from Ca to Ni and are emitted with energies of the order of 60 mev. It is gratifying to note that after the writer had postulated such a process for the origin of coronal emitters, ternary and quarternary fission were reported by Lark-Horowitz (1941) and theoretically treated by Present (1941).

TABLE 4*

STRIPPED IRON IONS AND THEIR ELECTRON STRUCTURE, ETC

Ion	Electron structure	Fundamental state	Value of the lowest terms in volts	$\sqrt{\frac{\text{I.P.}}{13{\cdot}54}}=\frac{z_i}{n}$	Remarks
$_{26}$Fe I	$..3d^6 4s^2$	$^5D_4$	7·83	0·76	
Fe II	$..3d^6 4s$	$^6D_{9/2}$	16·5	1·10	Forbidden lines found in η Carinae. 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	$..3d^3$	$^4F_{3/2}$	..	(2·69)	,, ,,
Fe VII	$..3d^2$	^3F	..	(3·01)	,, ,,
Fe VIII	$..3d$	^2D	150·4	3·33	$^2D_{3/2}-^2D_{5/2}=1875$ 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 $^2P_{3/2}\leftarrow{}^2P_{1/2}$.
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 $^2P_{1/2}-{}^2P_{3/2}$.
Fe XV	$..3s^2$	$^1S_0$	454	5·79	No metastable state.
Fe XVI	$..3s$	$^2S_{1/2}$	487	5·99	,,
Fe XVII	$..2p^6$	$^1S_0$	1259·7	9·65	,,

*Reproduced from the author's paper, "On a physical theory of the solar corona," *Proc. Nat. Inst. Sci.* **8,** 99, (1942).
†Parentheses ( ) denote that the value is extrapolated.

It can be shown that if one of the heavy fission-elements undergoes a ternary or a quaternary fission, the fragments, after a number of β-emissions, will be elements from Ca to Ni (the limit on both sides is rather elastic), and they will be emitted with an energy of approximately 60 mev., i.e., in the case of Fe atoms with a velocity of 6·4 $c\alpha$. Let us now turn to table 4, which shows the velocity of the outermost electrons of iron, and its ions. We find that the 2 p-electron of Fe XVII has a velocity of 9·6 $c\alpha$. This will therefore be retained, but if we take Fe XVI, the $3s$-electron is found to have a velocity of 6 $c\alpha$. We can therefore conclude that in a fission process of the type envisaged here, occurring in the reversing layer, the iron atoms which normally have the electron composition $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^6\ 4s^2$ will have lost the outer 15 electrons, namely, $3s\ 3p^6\ 3d^6\ 4s^2$, and will start as Fe XVI with the electron composition $1s^2\ 2s^2\ 2p^6\ 3s$. It will now be interesting to follow the physical processes to which such a highly charged ion produced anywhere in the sun can give rise, as it passes through the solar atmosphere. These are:

(*a*) *Ionization by collision.* The ion goes on knocking electrons and nuclei from the atoms which it encounters in its way, just as an α-particle does when it is projected in a cloud-chamber. In this process, the ion continuously loses energy, and it is possible to calculate its *range* with the aid of the Bohr-Bethe formula (1936), provided we assume that the solar atmosphere consists mainly of H atoms with few C and N atoms (as given by Menzel). The range is found on certain plausible assumptions to be $R_H \simeq 1{\cdot}31\times 10^{21}$ H atoms/cm.^{2} for Fe XVI projected with a velocity of 6·4 $c\alpha$.

We can draw very important conclusions from this calculation. Nuclear processes giving rise to Fe XVI, or similar highly charged iron or other ions may occur throughout the whole *solar interior*, but most of such particles have no chance of ever passing out of the solar atmosphere. Most of them will stop dead earlier. If the number of H-particles in the reversing layer is taken to be $1{\cdot}8\times10^{22}$/cm.^{2} (Unsöld, 1939), R_H is far less than this number, and it is obvious that only those fission particles which are produced rather high up in the "reversing layer" have a chance of escaping through the chromosphere and emerging into the inner corona.

(*b*) *Possibility of the further loss of an electron by the ion.* The Fe ion may itself lose a further electron by collision with atoms, but the probability of this event vanishes when the velocity of the ion reaches a certain limiting value. For the solar atmosphere, the limiting velocity, under certain plausible assumptions, is $V_c \simeq c\alpha.z$, where z is the net charge on the ion. The Fe XVI ion cannot therefore lose any further electron.

(*c*) *Capture of electrons by the ion.* The Fe XVI may capture an electron from any one of the atoms in its path, or even a free electron, and become Fe XV: $1s^2\ 2s^2\ 2p^6\ 3s^2$ (normal) or $3s\ nx$, where nx is a higher orbit. The probability of the capture at first increases as the velocity of the ion diminishes. When the capture is in an excited orbit, the iron is expected to execute one or more quantum transpositions, emitting x rays, and ultimately we shall have normal Fe XV. This has no metastable levels, so no visible radiation can be emitted by Fe XV.

The Fe XV ion will now pass through the same career as Fe XVI, but the electron composition of the next ion formed is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p$, and hence we have two metastable levels, $^2P_{\frac{1}{2}}$ and $^2P_{\frac{3}{2}}$. The strong coronal line λ5303 is due to the forbidden transition $^2P_{\frac{3}{2}} \rightarrow {}^2P_{\frac{1}{2}}$. The emission of λ5303 necessarily indicates that some amount of x radiation due to the allowed transition $3s^2nx \rightarrow 3s^23p$, $\lambda \simeq 80$A., is also being emitted. The capture can take place at all velocities of Fe XV, from $s=6$ down to $s=0$, but the formula of Brinkmann and Kramers has been worked out only for capture in S-orbits and for high velocities of the ion. It has still to be worked out for small s and for capture in p-orbits; hence at this stage it is not possible to give any quantitative estimate. The next ions from Fe XIII to Fe X are all formed by successive capture of electrons from the solar atoms or of free electrons in the solar atmosphere, and thus the $3p^x$-shell is formed ($x=1$ to 5), which gives us the coronal radiation given in table 2.

The possibility of any one of the Fe XIV to Fe X ions emerging out of the chromosphere to the coronal heights therefore depends upon: (*i*) the probability of a fission of the type mentioned above taking place in the sun, (*ii*) the region where the fission takes place. Bohr and Wheeler (1940) have shown that only heavy nuclei like ^{238}U, ^{235}U, ^{232}Th, ^{229}Pa are capable of fission. These can occur in the solar interior as well as in the reversing layer, but ions formed in the interior are stopped dead earlier, and only such as originate in the reversing layer can escape to coronal heights. The origin of the coronium emitters is therefore to be found in the upper part of the reversing layer.

At this stage some of the probable doubts and objections in the mind of the reader may be anticipated:

(1) Have we in the sun's atmosphere or interior sufficient U or Th atoms, which alone have been shown by Bohr and Wheeler (1939) to be capable of fission by neutron-bombardment ?

U has not yet been traced in the sun, probably owing to the extreme complexity of its spectrum. But the presence of lines of singly-ionized Th has recently been definitely established by Moore and Babcock (1943).

(2) Why should we get only Fe, Ni and Ca in the corona, and not any of the contiguous elements, say Co, Mn, or Cu, A or K ?

An investigation carried out by D. Kundu (1942) at Calcutta shows that Fe, Ni and Ca are spectroscopically better suited for identification than any other elements in this group excepting Co. But Co is probably represented by a faint line in the corona, λ4359, which Kundu attributes to Co XV. Subsequently, through the courtesy of the Astronomer Royal of England, the writer has been able to have access to a copy of Edlén's paper (1942) in which the same opinion has been expressed.

But even if Co, Mn and other elements of the group are subsequently found to be represented by some of the fainter coronal lines not yet identified, it is clear that these elements are represented far less strongly than Fe, Ni and Co. Edlén has tried to connect the phenomenon with the so-called cosmic frequency of elements. But probably the real reason is that in a nuclear process there is a greater probability of the occurrence of even-numbered atomic elements than of odd-numbered ones. Each one of the former is represented by four or more isotopes, but the latter generally (for example, Sc, V, Mn and Co) by a single isotope. There is, therefore, a greater chance of fission products ultimately transforming themselves after β-emissions to Fe, Ni and Ca than to Co, Mn and Sc.

(3) Why do we not observe the forbidden lines of Fe ions from Fe IX to Fe II, and of the corresponding ions of Ni, amongst the coronium-lines ?

Fe IX has no metastable state and Fe VIII has the composition $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d$. The ($3d\ ^2D_{\frac{3}{2}} - {}^2D_{\frac{5}{2}}$) separation is too small to give a line in the visible range. Some of the forbidden lines of Fe VII to Fe III having the composition of $3d^x$ have been traced by Bowen in the nebulae, and of Fe II in η Carinæ, and by Merill (1943) in BF Cygni and other stars; Kundu thinks, too, that some forbidden lines of Fe V can be identified with fainter, doubtful lines in the solar corona. But these doubtful lines require further investigation, both as regards wave-length measurements and identification.

It is clear that even if subsequent investigations prove that the forbidden lines of the $3d^x$-complex (Fe VIII to Fe II) occur in the corona, they would prove to be extremely faint compared to the forbidden lines of the $3p^x$ combination. This may be due partly to the fact that the probability of capture of an electron in a d-orbit is far smaller than that in a p-orbit. Exact calculations are difficult and are being carried out, but the finding is questionable.

The complete establishment of these ideas will require a colossal amount of experimental and theoretical investigations, the nature of which is clearly indicated in the text. But the value of the hypothesis can also be assessed from a discussion of its bearing on the associated problems of the solar corona mentioned earlier.

If the considerations presented here regarding the origin of emitters of coronium lines prove to be correct, it is obvious that the electrons constituting the inner and outer corona are simply the δ-rays liberated by the coornium-emitters (Fe XIV and others) from H and other atoms in the upper reversing layer, and the chromosphere in the process of ionization by collision as these highly charged emitters of coronium lines pass through the solar atmosphere. The velocity of these electrons is given by the relation $V_e = 2V_i \cos \phi$, where V is the velocity of the ion and ϕ the angle between the direction of emission of the δ-electron with the original direction of motion of the ion. It is clear that $V_e \simeq 2V_i \simeq 2c\alpha s$, and may have as high values as $2c\alpha$. The swifter electrons are mostly emitted inside the reversing layer and inside the chromosphere, and will be able to escape with velocities of the order $2c\alpha$; they probably constitute the electron atmosphere which we know as the corona. The theory has evidently to be further worked out to yield more details about the corona.

The coronal problems are almost unique in astrophysics, because if we leave out the sun, the coronal lines are not observed in the very wide range of astrophysical phenomena; neither in spectra of normal or peculiar stars, nor in those of novae or supernovae, except in the solitary case of recurrent novae (RS Ophiuchi), as was discovered by Adams and Joy (1933), and confirmed by Swings and Struve (1943). But it is inconceivable to think that the sun should be a solitary exception. Probably the same physical processes which give rise to coronal lines are occurring everywhere, but the scale, compared with those of ordinary stellar emission, is far too low for the lines to be observable. We are able to observe them on the sun merely on account of our proximity to this star, and that only on special occasions (time of total eclipse) or by special devices (Lyot).

Is it possible to give more definiteness to the question of the *scale* of coronal emission compared to those of ordinary photospheric or chromospheric emissions ? The photosphere emits 1500 cal./sec. per cm.^{2} of its area, the chromospheric emissions in Hα come to about $\frac{1}{50}$ of the corresponding photospheric emission in Hα, and according to estimates of Lyot, the coronal emission in the green line is of the order of 10^{-6} A. of the corresponding photospheric emission.

The ideas presented in this lecture may be compared with those of Rosseland (1934):

"Considering, for instance, the most familiar case, that of the sun, it is surprising how few theories are of such an obvious character as to deserve unreserved applause. It will probably be admitted generally that the interpretation of the origin of Fraunhofer lines is now so far advanced that a revision of fundamental principles may be unnecessary in this field. Proceeding a little further to the interpretation of spectroheliograms, the ground is already getting considerably more insecure. And when we proceed still further, we meet the enigmas of the sunspots, the prominences, the chromosphere, and the corona, none of which can at present be said to be understood, even in the most liberal interpretation of the term.

"The enigmatic character of these phenomena is not so much concerned with the generally admitted fact that we do not understand their common cause, which underlies solar activity as a whole. It is more that we do not know how to interpret the individual manifestations in an intelligible manner. We know of no simple mechanism at present according to which magnetic fields of the magnitude observed in sunspots could be generated. The motion of prominences is recognized as quite different from any motion which could be produced by the combined action of gravitation and electromagnetic forces on a mass of gas in a vacuum, and the agglomeration of matter in the corona surpasses by billions the amount to be expected on any simple hydrostatic theory. These various facts have stimulated speculation to the breaking point, it being even suggested that here we witness our recognized physical laws set at naught by nature herself. Although these speculations are not likely to be taken very seriously by the experienced physicist, they bring out forcibly the unsatisfactory state of solar theory today."

Rosseland's view in 1934 was: "Chromosphere, corona and prominences would in that case form a complex of dynamic phenomena, the theory of which must be based on considerations of the expansive motion of matter moving away from the sun in a more or less radial direction. It does not follow, of course, that all matter in a streamer is moving with the same velocity."

Rosseland concludes: "Though we definitely do not know the nature of these primary particles, the existence of which is indicated by general arguments, there are reasons to believe that they are electrically charged."

Rosseland has considered the equilibrium (?) of the electrified atmosphere, but the physical factors introduced (for example, resistance to the motion of positively and negatively charged particles) are of a vague character. Probably the ideas introduced here will impart definiteness to these factors.

The idea of temperature-equilibrium can be applied to the photosphere and the reversing layer, and that, too, very approximately. The general chromospheric phenomena and other associated ones like prominences are probably partly due to temperature, partly to radiation pressure, and probably nuclear reactions giving rise to α-particles and protons play some part. The coronal phenomena are of a different type—arising from a process akin to or identical with fission, and they are just like rocket-bursts in our atmosphere. The three types of phenomena intermix and produce a complicated picture.

The author had the privilege of discussing the theory of the corona given here with Professor Dirac during a short visit to Cambridge. Dirac made the most interesting suggestion that the β-rays emitted by the fission products may turn out to be the high-energy electrons which are wanted for explaining auroral phenomena. For it is well known that Störmer's theory of the aurora has not been able to explain why the zone of maximum frequency of the aurora is at a distance of 22° from the magnetic poles (see Hewson, 1937). This proves that the corpuscular rays responsible for the auroral phenomena cannot be photo-electrons, or even β-rays of moderate energy. They can be either β-rays of energy of the order of 5 to 10 mev. or α-particles, but the last possibility is generally ruled out on other grounds. The β-rays expected to be given out by fission products have the requisite energy, but there are other factors, and the problem may be left at this stage.

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