IN MEMORIAM

In memory of the scientist of international repute and a keen student of Indian history, philosophy and social institutions, the Asiatic Society decided in 1957 to bring out a special issue as the Meghnad Saha Number, containing papers both on science and letters.

Dr. Saha gave evidence of his remarkable genius not only in the field of pure science but also in its application for the good of humanity. As an academic scientist he earned the highest reputation by his 'Theory of Ionization in Solar and Stellar Atmosphere' and as a constructive academician he immortalized himself by establishing the Nuclear Institute of Physics under the auspices of the Calcutta University and the All-India Academy of Sciences in Uttar Pradesh. As a nation builder and a constructive thinker he revealed his far-sightedness in his plans and writings about the River Valley Schemes, particularly those about the Damodar and the Ganga Barrage, and in his tenacity and insistence on Dr. B. C. Roy for materializing the Durgapur project.

Dr. Saha was an uncompromising critic and in his Lok Sabha speeches he did not even spare the Prime Minister, who, however, in spite of his criticisms, had a soft corner for him for his scientific knowledge and extended his helping hand to the fulfilment of his ideas and schemes. His last but not the least achievement was the Calendar Reform. He was indeed a born fighter for the cause of science and humanity and a constructive genius with a forceful personality. Our country and particularly our Society has suffered an irreparable loss by his untimely demise. May his soul rest in peace.

N. Dutt,
President.

DR. MEGHNAD SAHA

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DR. MEGHNAD SAHA

Dr. Meghnad Saha, F.A.S., D.Sc., F.N.I., F.R.S., was born at Dacca in 1893. His parents were not in affluent circumstances and the cost of his education throughout his school, college and University career he met himself from the scholarships and stipends he won by his brilliant examination results. Saha took his M.Sc. degree in Applied Mathematics from Calcutta University in 1915 and got his D.Sc. from the same University in 1918. He was one of the band of young workers who, on the invitation of the late Sir Asutosh Mookerjee, joined the newly founded University College of Science in 1916 as a Lecturer. In 1921 he was appointed Khaira Professor of Physics, but left Calcutta University in 1923 to join the University of Allahabad as Professor and Head of the Department of Physics. He stayed in Allahabad for fifteen years, returning to Calcutta in 1938 as Palit Professor of Physics. This post he held till 1952 when he was appointed Director of the Indian Association for the Cultivation of Science. It was while serving in this capacity that Saha breathed his last on 16th February, 1956.

Dr. Saha was first and foremost a scientist, and that of a very high calibre. He was also an author and a writer, a great organizer, a philanthropist and reformer and last, but not the least, an ardent patriot.

The scientific work that won him world-wide recognition was that on the theory of thermal ionization, developed in 1917 when he was barely 26 years old. Like all great discoveries the theory is simple in its essentials and can be understood by any intelligent person. If heat is added to matter, its general effect is to loosen its component parts. A solid when heated turns into a liquid. The liquid on heating becomes vapour consisting of discrete molecules. On further heating, the molecules in the vapour break up into their constituent atoms. Saha argued that if the addition of heat be continued still further, then since electrons (carrying negative charge) are one of the constituents of the atoms they will be detached from the atoms and the atoms will be positively charged or ionized. Saha thus conceived the idea of applying what is known as the law of reversible action in chemistry to a hot mass of gas consisting of molecules, dissociated atoms—neutral and ionized—and electrons. With the help of the formula so obtained he could calculate the percentage concentrations of the 'dissociated' components as a function of the temperature and pressure of the hot mass of gas. The application of this so-called Theory of Thermal Ionization to the spectra of celestial bodies immediately brought order in a host of uncorrelated data of the molecular and atomic spectra. This work won for Saha the coveted Fellowship of the Royal Society of London in 1927 at the young age of thirty-four.

Dr. Saha was the senior author of two well-known scientific works. His *Textbook of Heat* has a world-wide circulation and has run through several editions. The other book, *A Treatise on Modern Physics*, published in 1934 was an up-to-date, comprehensive work on the subject at the time it was published. Besides, Saha had written numerous articles on subjects of scientific and economic interest up to his very last days. I might mention in this connection the brochure 'Re-thinking Our Future' published in 1954, a very thoughtful and constructive criticism of the problem of planning.

For organizational work Saha had few equals. He would not rest till he had given practical shape to the idea he had in mind. I might cite some instances of this. While in Allahabad he successfully pleaded with the U.P. Government for the establishment of the U.P. Academy of Sciences. Those who know how unapproachable the bureaucracy of those days were would appreciate how persistent the effort of Saha must have been to achieve his objective.

From Allahabad he used to come down often to Calcutta for purpose of founding a scientific journal on the line of the *Nature* of London. He argued that without such a journal, the scientists of the country could not place their views on scientific matters and on the utilization of science, either before the Government or before the public. His efforts were crowned with success when, in 1935, was founded the Indian Science News Association with its mouthpiece *Science and Culture.*

Dr. Saha had been instrumental in the founding of the National Institute of Sciences of India against many odds. I was present with him in England when he sought for and obtained an interview with Lord Ronaldshay, the then Secretary of State, for obtaining recognition of the Institute as the representative national scientific body of India.

The founding of the Indian Physical Society in 1934 is another of his achievements. And, last but not the least, the establishment of the Institute of Nuclear Physics and the striking expansion of the Indian Association for the Cultivation of Science by securing funds from the Government, are lasting monuments of his organizing ability.

Dr. Saha's love for his motherland—his patriotism—was rational, with a scientific outlook. He wanted his country to be free not only from the foreign yoke, but also from the grip of the trio—poverty, ignorance and disease. His advanced views on the former, brought him, when he was still a student, into conflict with the then governmental authorities. He was refused permission to sit for the competitive examination of the Indian Finance Department. This was, of course, a blessing in disguise. The country perhaps lost an able finance officer, but surely gained a scientist of eminence.

Saha's burning desire to see his country freed from poverty and its attendant evils led him to plead for planned economy, for forced march to bridge the gap of 150 years by which we are behind the advanced countries of the West. Saha drew the pointed attention of the country to the root cause of mass poverty. He argued that this was due to our not making full use of the natural powers for productive purposes, being reliant mainly on man and animal power. He maintained that the only way of driving away poverty is to industrialize the country and that quickly and extensively. It was at Dr. Saha's instance, in fact, that in 1938, the late Subhash Chandra Bose, the then President of the Indian National Congress, founded the National Planning Committee with Jawaharlal Nehru as its Chairman. The same rational, patriotic outlook of his made Saha agitate for the establishment of the so-called River Valley Projects by which a River of Sorrow like the Damodar could be turned into a River of Bounty. It was largely through his efforts that the Damodar Valley Corporation came into existence on the model of the Tennessee Valley Authority of the U.S.A. About the multiplicity of the benefits of the T.V.A.—flood control, irrigation, electrical power generation and recreational facilities—it was Saha who drew the attention of the public to it by his articles in *Science and Culture* and in the newspapers.

Saha's patriotism led him, in recent years, to enter into the public life of the country as a Parliamentarian. He got himself elected because—he confided to me on the eve of his electioneering campaign—he could then plead more forcefully and more effectively for the cause of science and for its utilization for the economic uplift of the country.

Dr. Saha's association with the Asiatic Society had been long and intimate. He became a member in 1928, was elected a Fellow in 1930 and was its President in 1944–46. I have particular reason to be grateful to him when he was President, because it was in this capacity that he arranged for the publication of my book, *The Upper Atmosphere*, notwithstanding the high cost involved.

Dr. Saha also used to contribute articles to the *Journal of the Asiatic Society*, his latest article being on 'Different Methods of Date Reckoning in Ancient and Mediaeval India and on the Origin of the Saka Era'. He prepared this article while engaged in the work on Calendar reform as a member of an International organization. The article incidentally shows his keen historical sense and his great interest in the study and research in history. With his prodigious memory Saha could recall dates of important historical events with an ease which would make any student of history envious.

It can be said most truthfully and without any exaggeration that the gap left by Dr. Saha would be extremely difficult to fill. It is rare to find in a person a combination, such as he had, of a profound man of science and an organizer of the highest ability, a man with boundless energy and determination, and of unlimited capacity for work. It is doubtful if such a man would be born even in a century. It is strange that a man of such grim determination would have a heart so sympathetic to the sufferings of his fellowmen. It was this trait of his character that made him take up the cause of the refugees—a cause for which he fought till the last day of his life. I cannot help recalling here a personal reminiscence illustrating vividly how soft his heart was. Dr. Saha and I happened to be in New York together in 1936. We knew that there was living in New York for many years a common acquaintance of ours. Some friends of mine in New York, however, warned me that this man had fallen to evil days and that if we went to see him he would only ask for a loan which he would never repay. So, when one day Dr. Saha suggested to me that we should go to see this man I warned him of what I had been told. But Saha said 'Well, suppose he asks for a loan—what of that? Why should we not give him something since he had been an old friend of ours?' I must confess I felt ashamed of having suggested that we would rather not see this man.

In Dr. Saha the country has lost a very great son, and I a very close friend, almost a brother.

S. K. Mitra

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A STRATOSPHERIC OBSERVATORY

By Harlow Shapley

As I write this note in celebration of the genius and scientific career of Professor Meghnad Saha, the news comes to me of the successful flight of Martin Schwarzschild's stratoscope. It seems very appropriate, therefore, to record my consultations with Professor Saha twenty years ago when he was a visitor at the Harvard Observatory. What could we do, we asked each other, with telescopes working above the main part of the earth's atmosphere? What about a space platform so high and steady that we terrestrials would have some of the advantages of observers on the moon? I remember that I worried somewhat about accepting for publication his resulting paper because he seemed to be dreaming about an impossibility—an observer in the sky, forty kilometres above the earth's surface. But I decided that we should go ahead with the printing of his note in the Harvard Bulletin, No. 905, because he had in the paper devoted himself not to the subject of artificial satellites or details of the launching of instrument-carrying balloons, but rather to the question of what we might be able to learn astronomically *if* we were operating a stratosphere observatory.

No particular attention was paid to Saha's paper, so far as I know, because in 1937 no one was making much progress in high altitude exploration. Rockets were not being taken very seriously. The need of detailed information about the earth's high atmosphere had not yet been inspired by the requirements of the military.

But now the stratosphere observatory—its nature and value—is common talk. The first two artificial moons have been realized. And many non-military reasons for attempting to materialize the Saha dream have come to light. Spectroscope-carrying rockets have opened up the extreme ultra-violet of the sun's spectrum. The equipment planned for the satellites of the future includes spectrographs.

Saha's 1937 paper dealt almost wholly with the problems of the far ultra-violet spectrum of the sun which the ozone barrier is now keeping from our earth-bound instruments.

Before considering Saha's paper in more detail, let us speak of the breakthrough in solar astronomy which is now accomplished through the researches of Schwarzschild. The project is sponsored and carried out by the United States Government's military agencies, together with Princeton and Colorado universities and the General Mills research foundation.

Schwarzschild's stratospheric operations were not aimed to solve the same questions that inspired Saha. The latter wanted to surmount the ozone barrier. Current research has shown that most of the stratospheric layer of triple oxygen molecules lies between twenty and thirty-five kilometres above the earth's surface. This ozone shuts off most of the sunlight (and starlight) of wave-lengths between λ 2950 and λ 2000, and in that interval in the solar spectrum much is to be learned. Therefore Saha's hypothetical observatory, to be effective, had to be about forty kilometres above the earth's surface—above most of the air and above practically all the ozone.

Schwarzschild, on the other hand, has not been trying to get through the O_3 barrier. He had no need of going so high. His first attempt is to work at an altitude of about 15 km. His endeavour was to rise, if possible, above the turbulence of our atmosphere which is worst at the earth's surface and is appreciable for the first 10 or 20 km. above it. He aimed at steadiness, not transparency.

It is well known, of course, that the temperature gradients and the convection currents in our atmosphere produce bad 'seeing'. The turbulence in the atmosphere makes it impossible to get a picture, let us say, of the sun's surface with the definition and fine detail that we could get if we worked from the atmosphereless moon or from whatever satellite we could get to move above most of the earth's atmosphere.

Schwarzschild's stratoscope 'observatory' involves a large helium-filled balloon lifting a specially designed telescope that dangles far below; and it requires also a rapid-fire moving-picture camera and a device for automatic-guiding by sunlight acting on photon tubes. It is now reported that his first attempt (three separate flights) has succeeded. Granulations of the sun's surface that until now were hazy appear sharp. Their diameters and structures can now be described in such detail that the character of surface turbulence is better understood than before.

The future of the stratoscope's work will naturally include further exploration of the sun's surface. It will presumably include a look at the moon, and eventually at the planets.

The successful initiation of the stratoscope can be taken as one of the International Geophysical Year's important scientific contributions.

The foresight of Professor Saha can be best presented by reprinting from the Harvard Observatory's Bulletin a considerable part of his article of twenty years ago. In the intervening two decades we have realized on many of Saha's spectroscopic predictions; we have made rocket explorations in and above the ozone barrier, but his pioneering analysis remains little known.

'It is well known that our observations on the spectra of the sun and the stars are limited to the redward side of λ 2900, the ultra-violet part being absorbed in the upper atmosphere, at a height of between twenty and fifty kilometres, by a layer of ozone (equivalent to 3 mm. of gas at NTP) now known to arise from the photochemical action of the ultra-violet rays of the sun on oxygen molecules. This amount of ozone, tiny as it is, is sufficient however to cut off the spectrum between $\lambda\lambda$ 2900 and 2200 almost completely, though absorption begins to be perceptible from λ 3200. Below λ 2060, the extinction of the spectrum is due to absorption by molecular oxygen and nitrogen. According to some investigators, there is a so-called window between $\lambda\lambda$ 2300 and 2100, but evidence on this point is divergent.

'The abrupt termination on solar and stellar spectra below λ 2900 has been a great handicap to the advancement of our knowledge of the heavenly bodies, because the information gained from the study of the spectrum beyond λ 2900 is not sufficient to explain the problems of stellar mechanisms operative there. To take one example: the great intensity of the Balmer series and the associated continuous spectrum in the chromosphere has given rise to a large number of speculative theories which have again and again been obliged to fall back upon certain plausible hypotheses regarding the strength of the Lyman lines. If these lines could have been observed, the problem of hydrogen excitation in the sun and stars would probably have received complete elucidation, and the problems of stellar atmospheres would have been nearer solution.

'It is therefore not surprising that when some years ago Cario (*Nature*, **122**, 810, 1928) made the suggestion that the North Polar region, being free from illumination by the sun during the winter, might not contain any ozone, and therefore observations carried out there might extend stellar spectra much further on the violet side of λ 2900, the suggestion was greatly welcomed. It was a disappointment for the astronomical world when observations by Rosseland (*Nature*, **123**, 207, 761, 1929) did not confirm Cario's hypothesis. The reason for this failure is now well understood, for Dobson and Götz (*Proc. Roy. Soc., Ser.* A, **122** [1929] and **129** [1930]), in their survey of the ozone content of the atmosphere at different latitudes, have shown that the amount of ozone in the atmosphere fluctuates with the season, rising at Abisko (latitude 68° N.) from 2·40 mm. in the middle of September to 3·6 mm. in the middle of March. There is thus actually an increase in the ozone content during winter. This fact, apparently at variance with the theory of the photochemical origin of O_3, has been satisfactorily explained by S. Chapman (*Mem. Roy. Met. Soc.*, **3**, No. 26, 1930). The explanation is roughly as follows: The solar rays not only form ozone, but also destroy ozone. Every quantum of light between $\lambda\lambda$ 1750 and 2060 produces, on being absorbed, two molecules of O_3 out of atmospheric oxygen. But this ozone absorbs strongly the light between $\lambda\lambda$ 2300 and 3000, and every quantum absorbed converts two O_3 molecules into three O_2 molecules after a number of subsidiary reactions. The actual number of ozone molecules existing at any time depends upon the equilibrium between these two groups of opposing reactions. It appears that during a polar winter, when sunlight no longer illuminates the upper atmosphere, the ozone molecules already formed continue to exist, the destructive agency having been withdrawn. One always incurs a risk in extrapolating, but, as far as evidence goes, it appears certain that during winter the atmosphere of regions a few degrees from the North Pole also retains its ozone screen, so that observations of stellar spectra (the sun does not come into view, as it is below the horizon) will have no chance of taking us beyond the limit attainable in more hospitable climates.

'*Regener's Work.*—The recent discovery by Götz, Meetham, and Dobson (*Proc. Roy. Soc.*, A **145**, 416, 1934) that the ozone screen does not lie between fifty and one hundred kilometres as was formerly thought, but is confined between twenty and forty kilometres, affords a definite opportunity of extending stellar spectra beyond λ 2900, as has actually been demonstrated by E. and V. Regener (*Phys. Zeits.*, **35**, 788, 1935). Professor Regener has developed a fine technique of sending into the upper atmosphere balloons carrying automatic recording apparatus for measurement of the intensity of cosmic rays. His highest record has been thirty-one kilometres where, according to the estimates of Dobson and Götz and confirmed independently by the Regeners, two-thirds of the total ozone remains below. In the course of his last reported work in 1934, he sent along with his cosmic ray apparatus a quartz-spectrograph provided with automatic shutters and pointed toward a matt surface below, which was illuminated by sunlight. The time of exposure was short, and the reflecting power of the matt surface for the ultra-violet rather feeble. In spite of these disadvantages they were able to show that with increasing altitude the spectrum extended further into the ultra-violet, and that at the greatest height reached by their apparatus the limit was extended by about a hundred units beyond the limit reached by the same apparatus for the same exposure on the ground. If the exposures had been longer, and the surface had had a better reflecting power for λ 2800, it is clear that the spectrum might have extended much further than the lowest limit attained so far. They also confirmed the findings of Dobson and Götz that most of the ozone is to be found between twenty and thirty-five kilometres, that above forty kilometres the total amount is one-twelfth of the whole, and that above fifty kilometres it is barely two per cent of the whole.

'The pioneering work of Regener has shown the practical possibility of having a "Stratosphere Solar Observatory". It can now be confidently expected that if a regular programme can be organized for sending balloons to a height of thirty-five to forty kilometres, provided with quartz, fluorite, and vacuum spectrographs of sufficient light-gathering power, our knowledge of the solar spectrum beyond λ 2900 will receive a great impetus. The Russian worker Moltchanoff claims that he has reached a height of forty kilometres with a balloon provided with Radio-Sonde signalling apparatus; it is therefore to be hoped that within the near future the problem of photographing the solar spectrum at a height of forty kilometres will be definitely solved.

'We conclude from the above discussion that a spectrogram of the sun, taken at a height of 40 km., will extend the spectrum to λ 2000, and probably no atmospheric bands will appear between $\lambda\lambda$ 2900 and 2000. Between $\lambda\lambda$ 2000 and 1700 the Runge Schumann bands of O_2 may appear in absorption. The region $\lambda\lambda$ 1700–1250 will probably be completely cut off. A strip between $\lambda\lambda$ 1250 and 1000 may be expected to be transmitted. Below λ 1000 no prediction can be made, as laboratory data are not available.

'But access even to these limited regions will result in invaluable additions to our knowledge, for they will afford information about the behaviour of the resonance lines of most of the elements which occur in the Fraunhofer spectrum and thus ease our way for the final solution of the mysteries of solar physics; e.g. we expect to get information (*a*) about L_α,λ 1216 of H; (*b*) about

$$\lambda 1640 \left(= 4R\left(\frac{1}{2^2} - \frac{1}{3^2}\right)\right),\ \lambda 1215 \left(= 4R\left(\frac{1}{2^2} - \frac{1}{4^2}\right)\right) \text{ of } He^+;$$

(*c*) about the existence or otherwise of the Li-continuum at about λ 2300; (*d*) about the resonance lines of elements from Be to O ($4 \rightarrow 8$); we shall not probably obtain any information about F and Ne, but we may obtain the Na-continuum. (*e*) As regards Mg, we shall obtain much desired information about the resonance lines of the elements Mg and Mg^+ which are just beyond λ 2900; (*f*) the same is true of the resonance lines of the elements Al to S. (*g*) We hope also to obtain very valuable information regarding transitional elements, particularly Fe^+.

'The above short account will indicate how much we should gain from a Stratosphere Observatory.'

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IONIZATION LOSS OF CHARGED PARTICLES AT LOW ENERGIES

By N. K. Saha

1. A General Review of the Ionization Phenomena

The properties and behaviour of ionized substances constitute a most fascinating field of study that has yielded some results of profound theoretical interest and great practical importance. In the stellar bodies the ionization of gases occurring under the influence of temperature and pressure appropriate to these bodies was treated by Meghnad Saha (1920, 1921) as a reversible chemical reaction and the theory of thermodynamic equilibrium of such reactions was developed by him in a series of classic papers. By combining in these works a remarkable knowledge of atomic spectra and reaction thermodynamics he obtained results of far-reaching importance which gave the only means to interpret the states of thermal dissociation of elements in the stars, their spectral emission, temperature and pressure and led to the classification of the stars in the principal sequences. The knowledge of the ionized gas and its dynamics has recently found its application in another important field, namely the working of a controlled fusion reactor. With increasing understanding of the problem of such a reactor it is now realized that nuclear fuels like D^2 or T^3 must be heated to ultra high temperatures of several 100,000,000°C. or more to obtain a state of complete ionization, i.e. a gas composed of free electrons and ions in equal numbers, in order that a fusion of such fuel nuclei may be achieved with a favourable energy balance (Post, 1956). Such a fusion reactor, if successful, would be the most potent source of energy for mankind to meet his rapidly growing power requirements for a good many centuries to come—till all the heavy waters of the oceans have been completely exhausted in the process. An intensive study of the (plasma) dynamics of the ionized light nuclei is, therefore, receiving urgent attention of the astrophysicists and the nuclear power physicists alike.

In the present article we are not interested in the specific problems of the ionized gases mentioned above, but in a different aspect of the ionization phenomenon, namely the ionization loss of energy suffered by heavy, penetrating, charged particles, like alpha-particles, protons, etc., in passing through gases and solids. In a sense this aspect of the phenomenon is very fundamental, as it aims at clarifying the mechanism of the ionization process as an electromagnetic influence on the atomic electrons. Side by side the theoretical studies are supplemented by laboratory experiments on ionization loss and penetration and stopping of the charged particles in various media, revealing valuable information on the structure of the atoms and interaction of the radiation field on the stopping medium.

The basic ideas in the theory of energy-dissipation of charged particles in passing through matter were given by Niels Bohr (1913, 1915) in his two classic papers. In these the kinetic energy of the swift ionizing particle is considered to be transferred to the atomic electrons through electromagnetic interaction which raises the atomic electrons to states of higher excitation and ionization. The limits of the interaction are introduced through 'collision parameters', the upper limit of which is provided by the adiabatic nature of the ionizing perturbation acting on the orbital electron. The treatment is essentially classical and non-relativistic and the results show fair agreement with experimental observations on the stopping power of alpha-particles in light gases.

In the later years while the basic picture of the ionization theory, as given by Bohr, has remained more or less unaltered, there has been substantial extension and refinement of the theory in several directions. Bethe (1930) gave a quantum perturbation treatment of the collision process with a view to removing the limitations of the classical treatment of the electron-orbital picture of the original theory. Bethe's formula gives the ionization loss of energy as

$$-\frac{dE}{dx} = 2B.N.Z\ ln\frac{2mv^2}{I}, \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

$$Z\ ln\ w = \sum_i \sum_k{}' f_{ik}\ ln\ w_{ik}\ , \quad B = \frac{2\pi z^2 e^4}{mv^2} \quad \ldots \quad \ldots \quad (1a)$$

where N is the number of atoms per unit volume of the atomic number Z, v is the velocity of the ionizing particle (M, ze), $I = \hbar w =$ the average excitation potential of the atoms, $m =$ mass of the electron and $v \gg ze^2/\hbar$ (criterion of the Born-approximation), and $E \gg MI/m$ (the particle energy is much great than electron energies in the atom). The quantum formula (1) gave somewhat smaller values of the stopping power which were in better agreement with experiments with α-rays at high energies than the results of the classical theory. A theoretical clarification of the relative merits of the classical and the quantum formula was, however, still wanting. This was achieved soon through the discussions initiated by Bloch, Bohr (1948) and Williams (1945) and the quantum calculations carried out by Bloch (1933) of the motion of the wave-packet in the Coulomb field of a point charge. These calculations clearly brought out the facts that for strong interactions one can introduce the classical orbital picture, but for weak interactions the classical description fails and a quantum perturbation treatment is appropriate.

Comparison with experiments showed that in the case of weak interaction, for H_2 and He, the formula of Bethe gave accurate predictions of the ionization loss and the range of the particles (except for low energies). For heavier substances, however, the agreement was less satisfactory, as Bethe's formula resulted in rather too low values of the average excitation potential.

A distinct step at this stage was Bloch's application of the Thomas-Fermi statistical model to the dynamics of the atom. This resulted in the evaluation of the average ionization potential, which when fitted into Bloch's simple formula, gave good agreement with experiments at high energies—protons of 100 meV or more. Minor deviations are observed in individual cases where the binding of the outermost atomic electrons are different.

Further refinement in the theory relate to the relativistic (Bohr, 1915) corrections necessary for the collision process, straggling in the energy loss, deflection of the electron (Bohr, 1915) (as the penetrating particle) in the field of the atomic nuclei and the effects of the polarization (Kramers, 1947) and static binding in the atomic fields. It will be out of place to go into details of these developments. Excellent survey articles covering the various theoretical developments and their refinements and corrections are available. Among others, mention may be made of the admirable summary up to 1951 by Bethe and Ashkin (1953) and up to June 1953 by Allison and Warshaw (1953), the theoretical review article by Uehling (1954) and the illuminating summary of the entire position by Lindhard (1955).

2. Ionization Loss at Low Energies

We shall now turn our attention to the ionization loss of energy and the range of protons at low velocities. The experimental works of Warshaw (1949) on the measurements of ionization loss in Al, Ag, Cu and Au for protons of energy from 400 keV down to 50 keV and of Madsen (1953) in the energy range of 2 MeV to 400 keV sufficiently cover the ground to permit a scrutiny of the theoretical position at low velocities. Clearly in this region the collisions acquire an adiabatic character for the more strongly bound electrons. Bethe's stopping formula (1) may not, therefore, describe the actual stopping process here. Further, the obvious difficulty of the form of the Bethe-formula is that the energy loss vanishes when $2mv^2/I = 1$, which is contrary to the actual experience. Bethe has given a correction to the atomic stopping power due to the K-electrons, but it does not seem to describe the behaviour of heavy atoms, nor give the correct stopping power down to quite low particle velocities. On the other hand Lindhard and Scharff (1953) have recalculated the ionization loss of charged particles on the Thomas-Fermi model of the atom. It has been admitted, however, that the apparent good agreement of their theory with experiment at low energies may not be justified, because when a more rigorous treatment is attempted on the Lenz-Jensen model, the agreement becomes much worse for low velocities. The problem is complicated at low velocities by the capture and loss of electrons which are difficult to treat theoretically, and have not been incorporated in any of the existing theories of stopping power.

The deviation of Bethe's formula from the experimental data at low energies mentioned above is strikingly brought out in the plot shown in curve I, Fig. 1, where the quantity

$$\frac{E}{N.Z}\frac{dE}{dx}\,(\text{keV cm.}^{-1}) = \frac{AE}{Z}\frac{dE}{dx}\,(\text{keV cm.}^2\,\text{mg.}^{-1})$$

is plotted against $\log_{10}(4mE/MI)$; E represents the particle energy $\frac{1}{2}Mv^2$ in keV and A is the mass number of the stopping element. The values of the ionization potential I for the various elements Al, Cu, Ag and Au which are used above are respectively 150, 279, 422 and 650 eV. The values for the first three elements are due to Bakker and Segrè (1951). For gold we have used the value 650 eV, which fits the experimental data quite well. Obviously, the validity of Bethe's formula requires the plot to be a straight line. The experimental points, however, clearly fall on a smooth curve considerably deviated from the expected straight line and approaching the latter only at medium energies corresponding to $\log_{10}(4mE/MI) \approx 0{\cdot}8$. For the various elements Al, Cu, Ag and Au the critical energy below which the deviation sets in is approximately 500 keV, 750 keV, 1·3 MeV and 1·9 MeV respectively.

A purely theoretical approach to the low energy problem is not feasible at the present stage. It seems possible, however, to modify the simple Bethe-formula empirically by introducing a multiplying factor F in such a manner that it should remove zero of the logarithm and also go to unity at high energies. That this is possible has been shown elsewhere (Kaila and Saha, 1956). Careful analysis of the available experimental data yields the required multiplying factor:

$$F = \frac{Z_{eff}}{Z}\cdot\frac{E^2}{E^2-E_0^2}, \quad \text{where } E_0 = \frac{M}{4m}I. \qquad (2a)$$

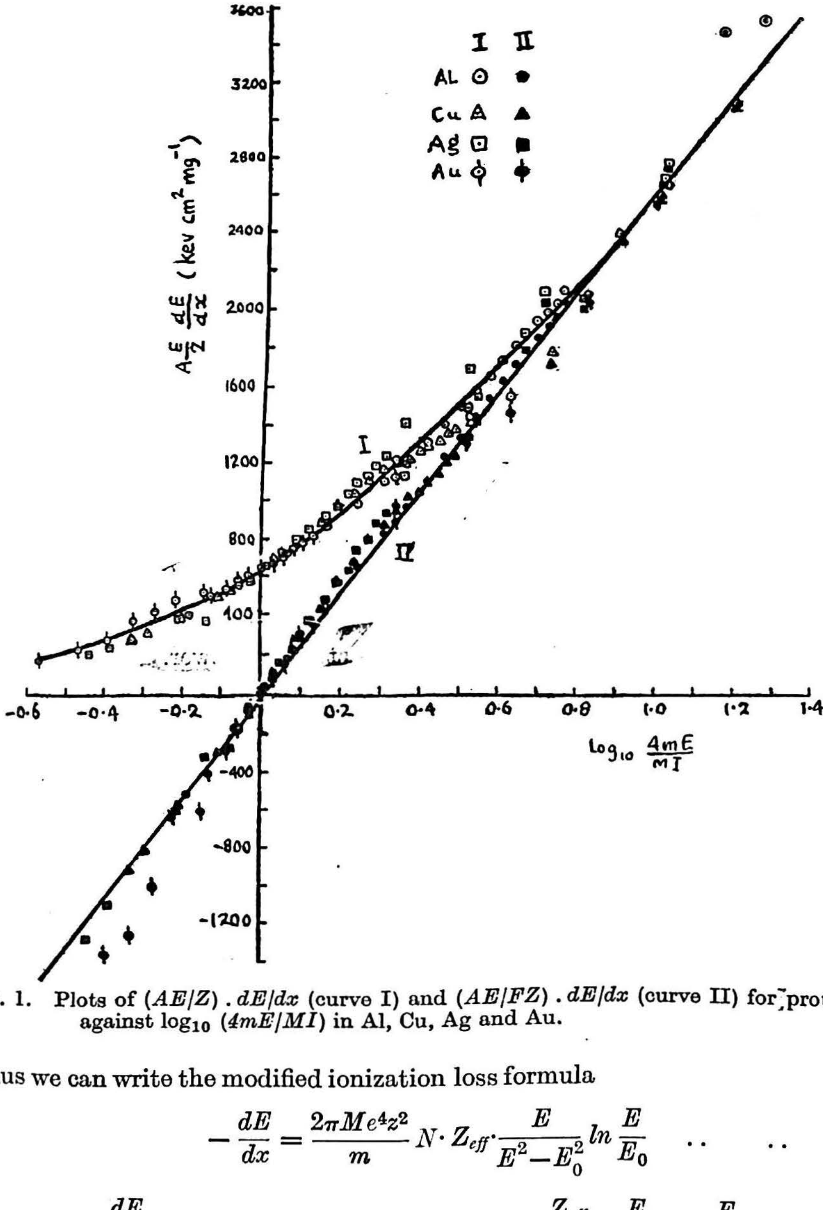

FIG. 1. Plots of $(AE/Z) \,.\, dE/dx$ (curve I) and $(AE/FZ) \,.\, dE/dx$ (curve II) for protons against $\log_{10}(4mE/MI)$ in Al, Cu, Ag and Au.

Thus we can write the modified ionization loss formula

$$-\frac{dE}{dx}=\frac{2\pi Me^4z^2}{m}N\cdot Z_{eff}\cdot\frac{E}{E^2-E_0^2}\ln\frac{E}{E_0} \quad \cdots \quad \cdots \quad (2)$$

or

$$-\frac{dE}{dx}\,(\text{keV cm.}^2\text{ mg.}^{-1}) = 14{\cdot}42\times10^4\cdot\frac{Z_{eff}}{A}\,\frac{E}{E^2-E_0^2}\ln\frac{E}{E_0}\cdot \quad \cdots \quad (2b)$$

This modified formula can now be tested in the light of the experimental data.

3. COMPARISON WITH EXPERIMENT

In view of the modified formula (2), if we now plot the quantity $(AE/FZ) \times dE/dx \cdot$ (keV $\cdot$ cm.$^2\cdot$ mg.$^{-1}$) against $\log_{10}(E/E_0)$ for the various metals over the proton energy range as before, we obtain the curve II in Fig. 1. The observed points, as marked on the curve, are seen to fall strikingly on a nearly smooth straight line down to about 50 keV (for Al). The deviation shown by Bethe's original formula at low particle velocities, therefore, vanishes in this modified form. The numerical values of dE/dx as calculated from the formula (2b) at different energies are shown in Fig. 2, where we have used $Z_{eff} = 0{\cdot}833Z$ by empirical fit with experimental value at one energy for Al. The dotted curves are the plots of Bethe's formula (1) shown for comparison. It is gratifying to note that the same value of Z_{eff} can be used throughout for all the elements investigated. Although the best fit is obtained for Al, Fig. 2(a), the agreement for the other metals Cu, Ag and Au, Fig. 2(b), is also

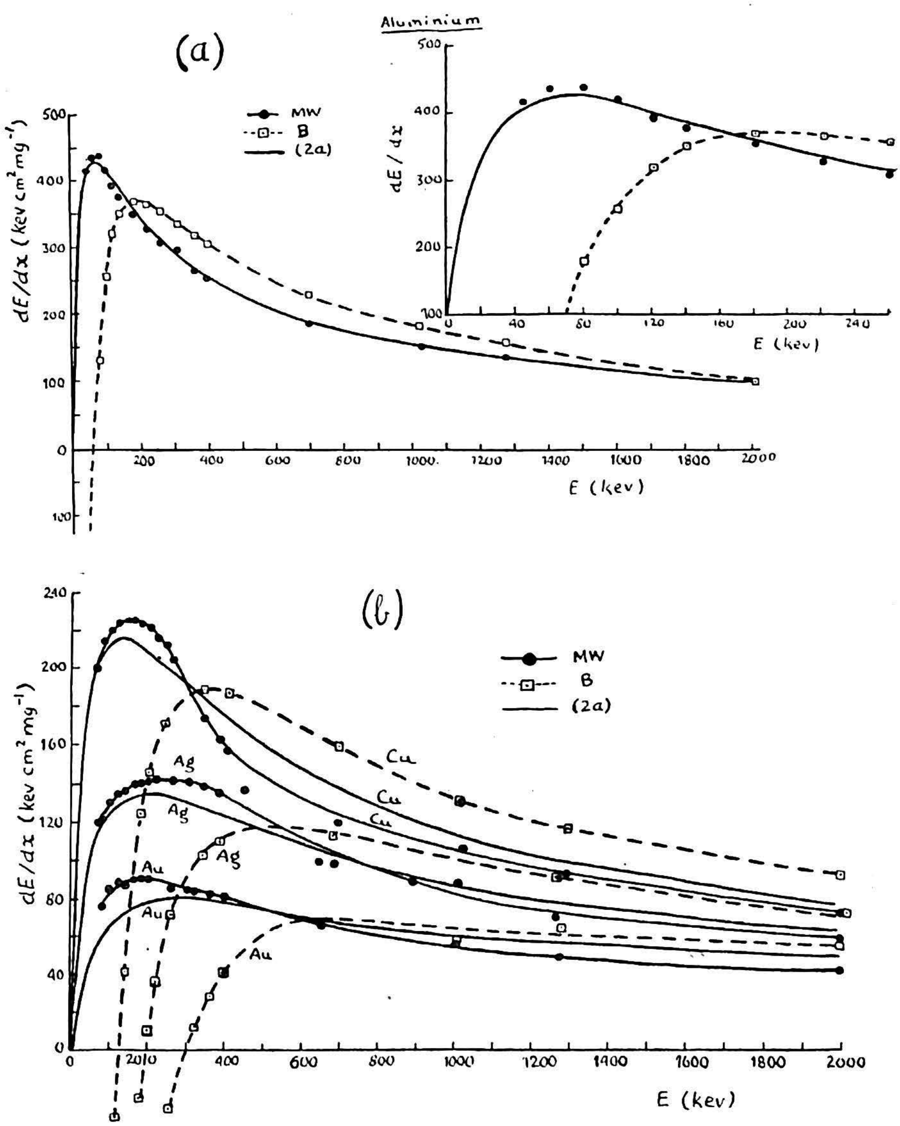

FIG. 2. Plot of dE/dx (keV cm.^{2} mg.$^{-1}$) at various proton energies in (a) Al, (b) Cu, Ag and Au. MW—experimental data of Madsen and Warshaw; B—calculated from Bethe's formula (1); full curves—calculated from formula (2a).

satisfactory. The comparison for Au does not stand on a very firm footing, as there is some uncertainty in the value of I used, as well as in the experimental data, as pointed out by Green, Cooper, and Harris (1955). For other details of comparison Kaila and Saha (1956) should be seen.

The range-energy relation for protons in the various stopping materials can now be obtained in a simple manner by using the modified ionization loss formula (2b) and the fundamental definition of range

$$R = \int_0^E \frac{dE}{dE/dR}.$$

For details of the calculation involving the energy intervals chosen and the method of solving the integrals Kaila and Saha (1956) is again referred to, where the plots for the calculated range-energy relations obtained for protons in Al, Cu, Ag and Au are given for the energy range $\sim$ 2000 keV to 140 keV. The result shows that within this energy range our calculated proton range in Al is 15 to 20 per cent higher than the values so far known from the curves given by Livingston and Bethe (1937). For copper the difference comes out to be still more. For Ag and Au no such previous range-energy relation exists for the low energy protons.

4. Ionization Loss of Protons in Gases

Similar calculations using formulae of the type (2b) have been extended by us to gases like air, oxygen, nitrogen and the rare gases neon, argon, krypton and xenon. It is found that by using $Z_{eff} \approx 0{\cdot}72Z$ and with minor adjustments in the constants, relations quite similar to (2a) give ionization losses of protons in low energy region for the various gases in fair agreement with the experimental values. Typical results of calculation for the proton ionization loss in air are reproduced in Table I.

Table I

Ionization loss of low energy protons calculated for air using formula of the type (2a)

Proton energy E (keV)	30	50	70	90	100	200	300	400	500	600
dE/dx (Bethe)	−6·43	+13·77	18·12	18·91	18·84	15·44	12·60	10·71	9·32	8·29
dE/dx (formula of the type (2a)) (eV . cm.^{2}/atom)	14·03	17·17	17·72	17·35	17·03	13·46	10·96	9·29	8·11	7·21
dE/dx (exptl.) ..	15·5	17·30	17·3	17·66	17·4	13·8	11·38	9·7	8·39	7·51

Results of calculation using Bethe's formula are also shown above for comparison. Over the entire energy range the results of the expirical formula (2b) give much better agreement with experiment than Bethe's. It is further noteworthy that relation of the same form should hold good for the solids as well as the gases. As has been pointed out by Bohr and Lindhard (1954), there is a large difference in the average charge of fission ions when emerging from solids and the charge of the ions of the same velocity when passing through gases. The dependence of the average charge of swiftly moving heavy ions on the density and pressure of the surrounding medium is considered to indicate that the balance between capture and loss of electrons by the ion involves not only its ground state, but also the excited states of a lifetime comparable with the intervals between successive collisions with the atoms. The ionization loss of low velocity protons seems to behave in a different way. This may mean that, contrary to the general belief, the process of electron capture and loss may not really be the dominant determining factor for the ionization loss of low velocity protons. There might be yet other unsuspected factors of primary importance involved in the process.

Fermi and Teller (1947) developed an elaborate statistical theory of slowing down and energy loss of charged mesons by the electron capture process in metals, insulators and gases. Their energy loss expression should be particularly valid when the particle velocity is below the critical value $v_0 = e^2/\hbar$, which for protons corresponds to an energy of $\sim$ 25 keV. Warshaw (1949) has used this formula to calculate the proton stopping power at energies between 0 and 25 keV in Ag and Au. Warshaw's experimental curves, extrapolated to low energies above 25 keV, meet smoothly the theoretical stopping power curves at about the critical energy 25 keV. But it seems that nothing definite can be said about the validity of the theory in this very low energy region, as direct experimental data do not exist here. It is interesting to note, however, as Warshaw has shown, that at higher energies (300–600 keV) a direct estimate of the net stopping power due to electron capture and loss by protons in Be accounts for only a deviation of < 1 per cent from values predicted from Bethe's formula, whereas the actual deviation of the experimental values is $\sim$10 per cent.

5. Discussion

The particularly simple form of the correction factor F arrived at by us deserves a few remarks. Although the real significance of the form of F cannot be understood unless the whole mechanism underlying the energy loss phenomena at low energies is clarified, its peculiar form may be suggestive of the unknown mechanism.

At low energies the most important process which is supposed to affect the penetration phenomena is the capture and loss of electrons. As discussed by Bohr (1948) and Bohr and Lindhard (1954), these processes dominate the field when the particle has a velocity of the order of the velocity of the atomic electrons. This occurs for protons at an energy of $\sim$25 keV. The capture and loss processes become important, therefore, only near the end of the proton range. At still lower particle energies ($\sim$a few e-volt) other processes besides the capture and loss of electrons become important. Thus a particle of kinetic energy lower than the lowest electronic excitation potential will excite oscillational modes of lattice or of individual molecules and thereby lose energy (Frohlich and Platzman, 1953).

The orthodox Bohr-Bethe-Bloch method of collision treatment of the stopping problem does not seem to be adequate to deal with all the above complicated low energy phenomena. The polarization effects are also not adequately treated by this method. Finally the collision treatment does not clearly bring out the connection of the stopping phenomena with other electromagnetic properties of matter.

Structure of the factor F, mentioned above, suggests that in certain limiting cases the treatment of the stopping problem should be based on the dielectric properties of a medium, as was first suggested by Fermi in 1924 and was later utilized by him (1940) in a treatment of polarization effects in distant collisions in the stopping of relativistic particles. In the wider context, the description of stopping phenomena by Maxwell's equations in matter seems to be a promising line of attack for the future.

As is well known, the first application of Maxwell's equations in matter was made by Frank and Tamm in 1937. The works of these authors could account for the Čerenkov radiation, discovered some years earlier, as that part of the energy loss which goes off in the form of coherent radiation. In the limiting case of particle velocity approaching the velocity of light, Fermi's (1940) treatment of energy loss in distant collisions by Maxwell's equations has shown a peculiar saturation of energy loss. Various other authors [Kronig and Korringa (1943), Kronig (1949), Lindhard (1954)] have later treated different aspects of the problem. But a general and comprehensive application of Maxwell's equations to the entire range of electromagnetic properties of materials is still wanting. Under such a scheme of treatment, it is hoped that the peculiar behaviour of the ionization loss of charged particles at low velocities may find its due place.

References

Allison, S. K., and Warshaw, S. D. (1953). *Rev. Mod. Phys.*, **25**, 779.
Bakker, C. J., and Segrè, E. (1951). *Phys. Rev.*, **81**, 489.
Bethe, H. (1930). *Ann. d. Phys.* (5) **5**, 325.
Bethe, H. A., and Ashkin, J. (1953). Experimental Nuclear Physics I, John Wiley.
Bloch, F. (1933). *Zs. f. Phys.*, **81**, 363.
Bohr, Niels (1913). *Phil. Mag.* (6) **25**, 10.
——— (1915). *Phil. Mag.* (6) **30**, 581.
Bohr, N. (1948). *Dan. Mat. fys. Medd.*, **18**, No. 8. (Review article.)
Bohr, N., and Lindhard, J. (1954). *Dan. Mat. fys. Medd.*, **28**, No. 7.
Fermi, E. (1940). *Phys. Rev.*, **57**, 485.
Fermi, E., and Teller, E. (1947). *Phys. Rev.*, **72**, 399.
Frohlich, H., and Platzman, R. L. (1953). *Phys. Rev.*, **92**, 1152.
Green, D. W., Cooper, J. N., and Harris, J. C. (1955). *Phys. Rev.*, **98**, 466.
Kaila, K. L., and Saha, N. K. (1956). *Proc. Phys. Soc. London*, **69**, 888.
Kramers (1947). *Physica*, **13**, 401.
Kronig (1949). *Physica*, **15**, 667.
Kronig and Korringa (1943). *Physica*, **10**, 406.
Lindhard, J. (1954). *Dan. Mat. fys. Medd.*, **28**, No. 8.
——— (1955). Niels Bohr and the Development of Physics. Pergamon Press, London, p. 185.
Lindhard, J., and Scharff, M. (1953). *Dan. Mat. fys. Medd.*, **27**, No. 15.
Livingston, M. S., and Bethe, H. A. (1937). *Rev. Mod. Phys.*, **9**, 245.
Madsen, C. B. (1953). *Dan. Mat. fys. Medd.*, **27**, No. 13.
Post, R. F. (1956). Controlled Fusion Research, etc., *Rev. Mod. Physics*, **28/3**, 338, July. (Review article.)
Saha, M. N. (1920). *Phil. Mag.*, **40**, 472, 809.
——— (1921). *Proc. Roy. Soc.*, A, **99**, 135.
Uehling, E. A. (1954). *Annual Rev. Nuclear Science*, **4**, 315.
Warshaw, S. D. (1949). *Phys. Rev.*, **76**, 1759.
Williams, E. J. (1945). *Rev. Mod. Phys.*, **17**, 217. (Review article.)