THEORETICAL PHYSICS IN THE UNITED STATES OF AMERICA

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PERHAPS the most important feature of scientific effort in the twentieth century is the simultaneous advance in fundamental sciences on the one hand and in technology on the other. This is particularly noticeable in the United States where despite the fact that technology has had such an impact on the amazing prosperity of the United States and scientific man-power is in constant demand by industry, fundamental research still engages the attention of the most gifted minds which emerge from its universities. As a typical example of this trend towards basic sciences, we shall consider the status of and contributions in theoretical physics in America today.

Physics deals with the study of matter and natural phenomena and such study consists of two parts:

(1) The precise measurement of physical quantities,

(2) Interpretation of such measurements and consequent understanding of natural phenomena.

The first part falls within the domain of the experimenter, the second, of the theoretical physicist. Till the advent of quantum mechanics, the connection between experiment and theory was quite direct, since the description of nature was based on classical concepts. But for a quantum mechanical description of matter, a complex mathematical formalism was introduced; no longer a 'pictorial' and 'conventional' method possible. Hence the relationship between experimental observation and the theories became more indirect and involved, perhaps even obscure except to those familiar with mathematical theories. On the other hand, the testing of these theories demand such precision in measurement that the experimenter had to devise new and ingenious techniques based on inventive technology and engineering.

The Universities in America realised this distinction quite clearly and soon became centres of fundamental research besides being just 'training grounds' for technical personnel in industry. With the vigour and initiative characteristic of America's growth and expansion, they invited talent from all parts of the world. The unhappy state of Europe during the turbulent period of the World War became a fortuitous circumstance for America's intellectual and scientific advancement—Einstein, Bohr and scores of leaders of scientific thought moved into the new world which was ready to imbibe the spirit and influence of basic research and fundamental science.

By the end of the Second World War, not merely the importance of mathematical sciences as 'tools' for technology, but their significance as an independent discipline necessary for the intellectual vitality and prestige of a nation was well realised. Theoretical physics became 'fashionable' and pure mathematics attained its 'queenly' pre-eminence. The 'competition' between the theorist and experimenter in suggesting 'leads' to the understanding of nature, led to very important theoretical discoveries and advances in experimental techniques. Laboratories supported by governmental aid and the co-operative effort of the Universities poured forth data on fundamental physical phenomena as 'food for theoretical speculation'. Thus the theoretical study and interpretation of such phenomena became an active pursuit and profession and ceased to be just the close preserve of the leisured savant and the profound natural philosopher.

In studying the progress of theoretical physics, it is convenient to classify it into three broad divisions:

(1) Formal and deductive approach to quantum mechanics,

(2) Interpretation of high energy phenomena and elementary particle interactions,

(3) Low energy phenomena and study of nuclear "structure".

1. Deductive Approach

The logical approach to quantum mechanics was initiated by Dirac with his formulation of the theory of the electron. While Heisenberg, Schrodinger and other architects of modern physics built up quantum theory by intuition and physical insight, Dirac was one of the first to make a formal deductive and rigorous formulation.

Encouraged by the successful prediction by Dirac of the positron and anti-particles

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in general, in the early forties theoreticians like Fierz, Pauli and Bhabha seriously attempted to "deduce" equations on a postulational basis. Though these attempts did not meet the desired success, they helped to inject more logic and rigour into theoretical physics. In the United States, Schwinger is the most famous exponent of the view originally expressed by Einstein that the axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented.

The deductive and logical approach naturally attracted the attention of pure mathematicians like Neumann and Weyl at the Institute for Advanced Study. The classic works of Neumann on the logical foundations of quantum mechanics and of Weyl on group theoretic methods are considered as part of the necessary equipment of any theoretical physicist today. But somehow, pure mathematicians did not make any substantial contribution to the content of quantum mechanics, presumably, as has been stressed in an interesting review of Hilbert's life, because of the fundamental difference between a mathematician's insight and a physicist's intuition. However, the abstract approach still holds the minds of many theoretical physicists and systematic attempts are being made to formulate field theory in a rigorous and deductive manner. The work of Nishijima and Wightman in the United States, the recent proofs of dispersion relations by Taylor, Oehme and others at the Institute for Advanced Study are examples of such attempts. Very recently, Heisenberg and Pauli have attempted to explain the mass spectrum of elementary particles by means of a non-linear spinor equation which has been quantised in a revolutionary way by making use of the indefinite metric originally due to Dirac. But it has to be conceded that despite the recognition of the necessity of a deductive approach to quantum mechanics, there is considerably widespread scepticism in the United States whether such approach will 'deliver the goods' in the near future. There seems to be more faith in the opinion of MaxBorn that the art of scientific prophecy can be learnt not so much by reliance on abstract reasoning as by deciphering the secret language of nature from nature's documents, the facts of experience.

2. High Energy Physics

The first major American contribution after the Second World War was in the field of quantum electrodynamics. By 1948, the application of quantum theory to electrodynamics initiated by Dirac two decades earlier reached a stage when theoreticians were faced with fundamental difficulties which needed essentially new methods and they were provided by the outstanding work of Schwinger at Harvard and Bethe, Feynman and Dyson at Cornell.

The quantum electrodynamics based on the classical concept of point charge gave rise to well-known difficulties such as the infinite self energy of the electron and the "ultra-violet catastrophe". Essentially connected with these difficulties are the infinite fluctuations of the charge and current in the case of matter field and the fluctuations in the field strength in the case of electromagnetic field even in the vacuum state. The existence of such fluctuations of charge and current in the vacuum implies that the vacuum acts like a polarisable medium which causes the phenomena of scattering of light by light or by electrostatic field.

Further progress in the subject came with the experimental discovery of the anomalous magnetic moment of electron by Kusch and the shift in the levels of the hydrogen atoms by Lamb and Rutherford, made possible by the war-time development of the electronic and microwave techniques. To understand these electrodynamic effects, it was found necessary to introduce the idea of renormalization of mass and charge. Suitable covariant renormalization techniques were developed by Schwinger, using formal field theoretical methods. Quite independently without any considerations of field theory, Feynman developed a most unconventional approach based on propagation kernels of single particles which was inherently covariant. His graphical representation of quantum mechanical processes, first applied to electrodynamics is now extensively used even in processes involving other elementary particles. The essential equivalence of Feynman's graphical approach and the formalism of Schwinger was established in a fundamental paper by Dyson. "The evolutionary process by which relativistic field theory was escaping from the confusion of its non-relativistic heritage has recently culminated in a new formulation of quantised theory of fields by Schwinger starting from a basic action principle". This also revealed that the connection between spin and statistics stems from invariance requirements.

By 1952, it was felt that quantum electrodynamics had reached a state of comparative completeness and it was not likely that future development will drastically change the results of electron theory which gave quantum electrodynamics a certain enduring value. "The real significance of the work of the past decade lies in the recognition of the ultimate problems facing electrodynamics, the problems of conceptual consistence and of physical completeness. No final solution can be anticipated until physical science has met the heroic challenge to comprehend the structure of the submicroscopic world that nuclear exploration has revealed". With the development of high energy machines in the post-war era, many phenomena were observed involving the creation of new and strange particles and high energy physics naturally included the study of these new processes like the production of mesons in nucleon-nucleon collisions and recently in electron-nucleon collisions, and the production of strange particles in high energy interactions.

The vast mass of data from the high energy machines from centres like Brookhaven and Berkeley raised a maze of problems as a challenge to the most gifted of theoreticians. The most famous of them all was the θ-τ puzzle—the identity of the masses and life-times of the two types of K-particles with different modes of decay and parity assignments. Dailtz's analysis of this puzzle claimed great attention at the Rochester Conference in 1956 and it is rather exciting to read the discussions after Yang's introductory talk in which Feynman, Yang, Lee, Bloch, Gellman and Marshak participated. It was of course given to Yang and Lee to question boldly the invariance of parity under space reflection in weak interactions and suggest the Cobalt experiment which was performed by Wu *et al.* and which brilliantly confirmed their predictions. Their remarkable paper reveals the new trend which characterises theoretical physics today,—the theoretical physicist having a live contact with experimental results and going so far as to suggest types of experiments to test the theories. More recently Yang and Lee have proved that analysis of the asymmetry in the angular distribution of the π decay will determine the spin of the Λ° particles.

During the study of weak interactions, the interest in the universal Fermi interaction has been revived to explain all weak interactions such as β-decay, μ^--capture and hyperon decay. Feynman and Gellman have proposed one such theory by extending the two-component formalism to all Fermi particles while Marshak and Sudershan have employed the "chirality" invariance to the same end. For all these theories the exact coupling between Fermi particles is of decisive importance. It looks at present that the vector and axial vector coupling will be preferred rather than the scalar and tensor. Pais and others are investigating the relative parities of the $K\pm$ and K° mesons.

While of course the theory of weak interactions claimed great attention following Lee and Yang's discovery, attempts are also being made to understand the strong interaction of heavy particles. Gellmann has proposed a global symmetry, *i.e.,* a universal pion-coupling between all heavy particles. He envisages a degenerate spectrum for the eight baryons in the presence of the pion-coupling. When the K-particle coupling is switched on, the baryons are split into groups as observed, *i.e.,* charge independent multiplets. Of course, the study of strong and weak interactions are included together in the former deductive approach mentioned before.

Meanwhile, there was another important theoretical development in the field of interactions of elementary particles involving strong coupling. In view of the evident breakdown of the perturbation theoretical approach to the study of interactions involving strong coupling, there was a long-felt need for a radically different method to tackle such problems. Goldberger at Chicago first realised the importance of the study of the analytic properties of S-matrix from general considerations and by the use of complex variable theory and in particular Hilbert's theorem he was led to relations connecting the real part of scattering amplitude to the integral over the imaginary part, the latter being related to the total cross-section. After a number of non-rigorous but intuitive derivations of such relations by Goldberger, Gellman, Salam and others, the dispersion relations for meson scattering by nucleons have been established in a rigorous way by Bogoliubov from U.S.S.R. and Bremmermann and others from U.S.A. The same approach has been employed in the electromagnetic and weak interactions especially by Bogoliubov. Goldberger is currently investigating dispersion relations for π-meson decay. The "dispersion relation" approach has been utilised to study nucleon-nucleon scattering, the electromagnetic structure of nucleons and similar problems by Goldberger, Chew, Nambu and others.

While high energy physics became fashionable consequent on Lee and Yang's discovery, non-relativistic theories at low energies also demanded considerable attention. Chew and Low's successes in the theory of pion-nucleon interactions exemplify such attempts. They have shown that if one assumes: (1) Pseudoscalar interaction, (2) Charge independence, (3) Negligible nucleon recoil, and (4) Predominantly P-wave interaction, then the crossing-symmetry, and unitarity of S-matrix are sufficient to establish the remarkable features of nucleon-pion interaction, in particular the resonance. The same method has also been applied for explaining photo-production of pions by utilising the gauge invariance characteristic of electromagnetic interactions.

Drell and others have extended the Chew's theory to include S-wave interaction which is strongly isotopic spin dependent, the nature of which is not fully understood. Chew's theory has also been applied to nucleon-nucleon interaction potential. Assuming only P-wave coupling, Gartenhaus has calculated the nucleon potential upto fourth order in the coupling constant. But this potential is inherently defective in that it does not yield any spin-orbit coupling. Recently, Marshak and Signell have proposed a phenomenological potential which simply consists of Gartenhaus potential *plus* spin—orbit interactions term obtained from phenomenological considerations.

As has been recognised for a long time, the knowledge of nucleon-antinucleon interaction is very essential in explaining the problem of nuclear forces. Attempts have been made to explain the large annihilation cross-section for N-$\bar{N}$. Chew's theory has also been applied to the problem of nuclear forces by Miyazawa from Japan, Klein and Mcormick from U.S. and Novoshilov from U.S.S.R. who have reduced the problem of two nucleon interaction to that of one nucleon. In recent years, the Compton scattering of protons have been re-examined from the point of view of Chew's theory.

3. Low Energy Physics and Nuclear Structure

While in the field of high energy physics we deal with the nature of elementary particles individually and their interactions, the collective properties of nuclear matter and the many-body problem of the nucleus (especially heavy nuclei) depends on data obtained from comparatively low energy phenomena. These theoretical considerations are usually referred to as "problems of nuclear structure"; the aim of which is to derive the nuclear energy levels, nucleon wave functions, imaginary and real potentials associated with the nucleus. In this, theoreticians have been puzzled for a long time by an apparent contradiction, namely, whatever we know about the nuclear forces indicates that these forces are very strong and have a dependence on position, repulsive cores, exchange character and other "peculiar" considerations. On the other hand, the properties of the nuclei at low energies both for bound states and for the interactions of nucleons with nuclei show the remarkable validity of the one-body approximation based on a very smooth potential without large magnitudes and large variation. This is the basis of many models which work so well, *e.g.*, shell model and the optical model. The apparent contradiction led some people like Teller and Johnson to go to an extreme point of view, *viz.*, to give up any connection between the structure of the nucleus and the nuclear forces as observed in nucleon-nucleon interaction. On the other hand, Brueckner and collaborators attempted rather successfully to resolve this contradiction. The essential merit of the outstanding work of Brueckner lies in that "it takes the nuclear forces as they are delivered to us and constructs from this a theory of complex nuclei, which gives us as good an approximation as possible in the one-body picture". Further contributions of Goldstein, Tobocman, Watson, Reisenfield may be mentioned in this connection. Professor Bethe is more inclined to the programme of Brueckner than the extreme point of view of Teller and Johnson. The experimental work relating to the optical model, the polarisation of neutrons at low energy and nuclear reactions involving light and heavy nuclei are being provided from various American laboratories. The emphasis of the theoreticians is still being felt in this field as in high energy physics. The contributions of Professor Lee on the theoretical implication of the parity violation in β-interaction followed by that of C. S. Wu on the experimental evidence of non-conservation of parity in β-decay at the Rehovoth Conference clearly indicate the very close connection between the fields of low energy and high energy physics. The discovery of parity non-conservation in weak interaction which originated in the θ-τ puzzle of the high energy phenomena has become very important in β-interactions.

In a wider sense, the study from a fundamental point of view of problems in different fields of physics has clearly demonstrated the inter-connection between them and the need for frequent exchange of views in conferences like those held annually at Rochester where both the experimenter and the theoretician are able to discuss the problems together. America has taken the lead in the organisation of such conferences, a lead soon followed in Europe, Japan and Russia. The proceedings of such conferences are considered sources as important as publications in scientific journals for future research.

It is the earnest hope of the young scientific community in India that at a time when our country is almost possessed by a desire for technological advancement, enough emphasis should be laid, as has been done in the United States on fundamental sciences as a necessary and independent discipline.

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