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Lectures in physics

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LECTURES IN PHYSICS

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General Editor

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FOREWORD

The last few years have seen an amazing number of discoveries in high energy physics. Availability of high energy lepton beams have played a crucial role in some of these discoveries as leptons, not having any strong interactions, constitute an ideal probe for hadron structure. Considering the fact that neutrinos were postulated by Pauli in 1930 and experimentally detected only in 1959 by Reines and Cowan, one has indeed come a long way now when we have intense beams of muon-neutrinos, and their antiparticles with which one can do experiments. Through deep inelastic scattering experiments with lepton beams on nucleon targets one has learnt of point-like constituents inside the nucleons. These experiments have not only elucidated the structure of hadrons; they have also led to the discovery of new interactions in which leptons take part. An exciting discovery was that of neutral current weak interactions in 1973.

The discovery of neutral weak current interactions, which were erroneously believed not to exist on the basis of absence of process $K_L^0 \rightarrow \mu^+ \mu^-$, is linked with theoretical upsurge of interest in the gauge theory idea.

Quantum electrodynamics has a very appealing inbuilt property that the phase of fermion fields can be chosen arbitrarily together with necessary redefinition of electromagnetic field potentials at each spacetime point i.e. the theory has gauge invariance of the second kind. In 1954 Yang and Mills in a celebrated paper showed how to extend this idea to the case of a theory with vectorially additive quantum numbers (i.e. when the internal symmetry group is non-abelian unlike quantum electrodynamics where it is abelian). Most people have found the Yang-Mills gauge theory idea both very tantalising and aesthetically attractive. It is tantalising since unlike most other concepts in high energy physics, it needs space-time continuum in a deep way for its formulation and as such, I believe, it is the only idea for which there is no pure S-matrix theory formulation. Its aesthetic appeal can be judged by the fact that despite many seemingly unphysical features, such as the presence of zero mass Yang-Mills quanta in the theory, theorists continued to pursue it for its own sake since its inception until the present time when it has finally made contact with high energy experimental physics. The difficulty of massless Yang-Mills quanta was solved through an understanding of Goldstone massless bosons and Higgs-Kibble mechanism discovered in gauge theories. Recent excitement dates from the work of 't Hooft in 1971 who 'showed' the renormalizability of gauge theories. Since these gauge theories of weak and electromagnetic interactions invariably imply neutral weak-current interactions, there was strong incentive to experimentalists to look for them. The talk of P. P. Divakaran is concerned with these and related developments.

The world of high energy physics was again full of excitement with the discovery of new hadrons, *J*/psi and psi prime at Brookhaven and SLAC in November 1974. These have masses of about 3.5 and 4.0 times the nucleon mass. Now hadrons of such large masses should live only for 10^{-23} seconds but these were found to live for some 10^{-20} seconds. For bringing the improbability of it all home imagine running into a man who has lived for some fifty thousand years. Such stabilities do involve generally some new quantum numbers. Faced with a similar situation in early fifties about the stability of what are now called strange particles, the resolution had been found by introducing a new linearly additive quantum number 'strangeness' by Gell-Mann, Nakano and Nishijima in 1953. It was natural to attempt a similar resolution for the new hadrons and a number of models such as the paracharge model, some versions of colour models and a model due to Yang were proposed in which the stability was attributed to these new hadrons carrying the new quantum number.

There are however other possibilities for understanding the stability of *J*/psi and psi prime hadrons. At the time of Pandit's talk on new hadrons the choice between the alternative possibilities was not available. Further experimental discoveries, especially that of *D* mesons, has however given support to the 'charm' alternative in which the stability of *J*/psi and psi prime is due rather to a dynamical rule, Okubo-Zweig-Iizuka rule, which seems to operate in hadron physics. While there is a new linearly additive quantum number charm, which is carried by *D* mesons, the *J*/psi and psi prime do not carry it. The charm model was introduced by Glashow, Iliopoulos and Maiani in an attempt to generalise to hadrons a very beautiful gauge theory model, due to Salam and Weinberg, of weak and electromagnetic interactions of leptons.

The talks of P P Divakaran and L K Pandit bringing the excitement of high energy physics to the fellows of Indian Academy of Sciences were given in the afternoon of November 8, 1975. The same evening G. Venkataraman delivered an evening lecture on "Fast breeder power reactors and their role in our nuclear power programme."

The world of high energy physics and the world of fast breeder reactors may look far apart from each other. It is interesting to recall the life of two pioneers Fermi and Bhabha here in this connection. Their fundamental contributions stand in high energy physics and are a source of inspiration.

But it was Fermi who initiated the nuclear chain reaction, leading to nuclear power, and it was Bhabha, another high energy physicist, who brought it to India and gave it shape in our context. According to a story, I heard from C. N. Yang, which to me as a high energy physicist appeared as sacrilegious, Fermi thought in his later years that he will probably be remembered for his work on the nuclear pile. Well, who knows! It is also sobering to reflect, as emphasised by Lewis Mumford, that mechanisation of the world picture, inspired by science, has finally caught up with science itself. There is no longer any very basic distinction between large high energy research laboratories and nuclear power plants. Indeed now we have meson factories and reactor research centres!

An analysis of available limited supply of coal, oil and natural gas and other conventional energy resources in India led Dr. Bhabha quite early to emphasise the role which nuclear power has to play in the development of our country. Speaking at the Second International Conference on Peaceful Uses of Atomic energy, Geneva, in 1958, he said: "One often hears it said that the underdeveloped countries will only be able to benefit from atomic energy after they have proceeded further with their industrialisation on conventional lines. I suspect that as a result of frequent repetitions of similar statements people have now come to believe them to be true..........." The perspective Indian planning has had to take into account the rather plentiful supply of thorium and the limited amount of uranium ore within the country. Breeder technology thus acquires a special place within our context. The present efforts were well described by G Venkataraman.

It is hoped that these talks will be useful to a wider audience.

VIRENDRA SINGH

Leptons and their interactions

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1. Introductory remarks

The term lepton denotes a fermion which has no strong interactions. As of today, there are four of them: the electron (e or e^-), the muon (μ or μ^-), both electrically charged, the electron-like neutrino (ν_e) and the muon-like neutrino (ν_μ) both neutral. Their antiparticles are distinct from themselves and are denoted by $\bar{e}$ or e^+ (the positron), $\bar{\mu}$ or μ^+, $\bar{\nu}_e$ and $\bar{\nu}_\mu$. All of them have spin half (in units of Planck's constant h). The electron has a mass $m_e=0.51$ MeV, while the muon is much heavier: $m_\mu=105.65$ MeV. The two types of neutrinos are generally assumed to be massless though the experimental upper limits are not especially small: $m\nu_e<60$ eV, $m\nu_\mu<1.2$ MeV. The electron and both types of neutrinos are absolutely stable, as far as we know. The muon decays, by weak interaction, exclusively according to

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu.$$

A remarkable feature of these particles is that the number of electron-like and muon-like leptons seem to be separately and absolutely conserved. It is convenient to state this property in terms of two quantum numbers: the lepton number N_l whose value is 1 for a lepton, -1 for an antilepton and 0 for all other particles and the muon number N_μ, 1 for μ^- and ν_μ, -1 for μ^+ and $\bar{\nu}_\mu$ and 0 for all other particles, including the electron-like leptons. In every reaction, N_l and N_μ are additively conserved.

As is clear from the title, the subject of this talk is the interactions of leptons (generally denoted by l) with themselves and with hadrons (h), that is to say, lepton-lepton and lepton-hadron interactions, both electromagnetic and weak (there is little definitive information as yet on the e.m. interactions of neutrinos). The non-leptonic aspects of the weak interaction, of which also we have little basic understanding now are therefore excluded from consideration here. I shall give only the briefest account of the earlier developments in this general area, highlighting the more fundamental experimental information on which the foundation of the subject rests and those theoretical insights which have proved to be of general validity and relevance. The more recent, exciting discoveries, both experimental and theoretical, will of course be the main focus of attention.

The *l—l* and *l—h* electromagnetic interactions are mediated by the photon (γ). I shall take it as given that the weak *l—l* and *l—h* forces are also carried by corresponding spin-1 bosons, the so-called *W*-bosons. Though these latter particles have not yet been detected in their free state in the laboratory, the recent theoretical developments in weak interactions make it clear, in my view, that their experimental discovery can only be a matter of time, as I hope to convince you presently. Thus, all *l—l* and *l—h* interactions are to be described in terms of primary interactions of them with photons and with *W*-bosons. The photon and the *W*-bosons differ from each other in two fundamental respects: a) the photon is a massless particle, corresponding to the infinite range of the e.m. interaction, while the *W*-bosons are very massive—we know that the weak forces have a very short range—this large mass perhaps being the reason for their not being produced and identified in the laboratory; b) the selection rules that govern weak interactions are such that the *W*'s must exist in more than one state—e.g., the well-known weak processes (such as β-decay) are mediated by charged *W*'s while the recently discovered neutral current interactions (to be discussed later) are carried by uncharged W's. These differences make for corresponding fundamental differences in the theoretical framework used in understanding them.

In discussing *l—h* interactions, I shall also use freely the idea that hadrons are composed of quarks and antiquarks, an idea with which you have become quite familiar from the lectures of Profs. Menon and Pandit. But here, it is necessary to remember that quarks need not be more than a semantic convenience. The concept of the quark and the way it is used to describe hadronic structure, as far as this lecture at least is concerned, need not be more than an attempt to reduce to the picturesque a set of ideas which can be precisely formulated in more abstract mathematical terms. In contrast to the situation regarding *W*-bosons, even if quarks are never discovered *in their free state,* it will not significantly alter much of the physics of lepton-hadron interactions.

2. Lepton–lepton interactions

A. Electromagnetic

The classic leptons are the electron and the positron and the dominant force between them is the electromagnetic one, given classically by the Coulomb potential (when the particles are static) and by the relativistic transform of this potential (when they are in relative motion). The quantization of a dynamical system consisting of electrons, positrons and the electromagnetic field results in the theory of quantum electrodynamics (abbreviated to QED from now on). The interaction between electrons (and/or positrons) is understood in terms of the emission and absorption of photons. There are of course also real photons which interact with other photons and with electrons and positrons. In the diagrammatic approach to QED invented by Feynman, the basic interaction is represented by a 3-leg vertex where the two solid lines denote the motion of an electron (or a positron) and the one wavy line that of a photon. This vertex may be thought of as the coupling of the electromagnetic current of the electron (formed by grouping the electron and positron "field operators") to the vector potential (the photon field operator). Any definite process is characterised by a given number of particles (of all three types) in the initial state as well as in the final state. Any way of joining the primary vertices to form a diagram, with the right number of initial and final free lines, then represents the process. For example, the simplest diagrams describing $e\bar{e}$ scattering (Bhabha scattering) are shown in figure 1. Clearly, one can make arbitrarily complicated diagrams by inserting more and more primary vertices internally, all describing the same process (there is a more abstract mathematical theory which gives a set of precise rules for the evaluation of the amplitude of a process arising from any diagram). Because, in QED, each extra vertex in a graph multiples the amplitude by an extra power of the coupling strength, which is the square root of the fine structure constant $\sqrt{\alpha} \simeq 10^{-1}$, more and more complex diagrams can be expected to make correspondingly smaller

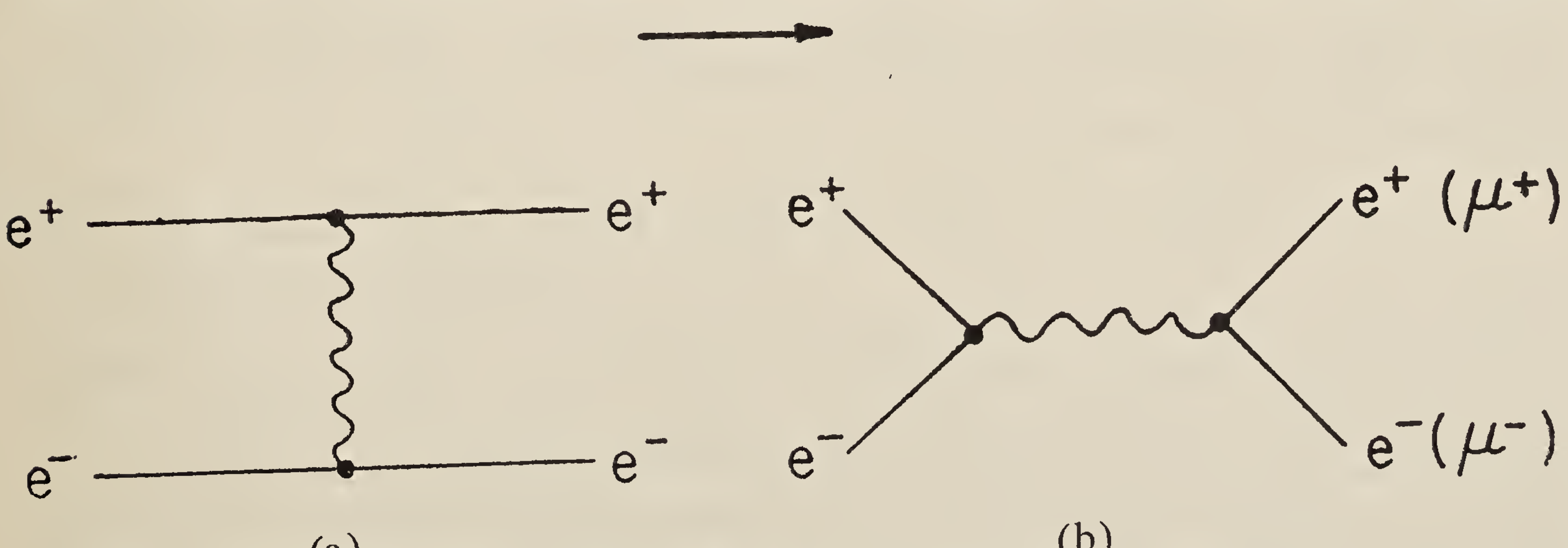


Figure 1. Bhabha scattering

corrections to the dominant contribution given by the lowest order (the simplest) diagram.

Unfortunately, when the first attempts to compute higher order corrections were made, it turned out that they gave apparently nonsensical infinite numerical answers. It is the great triumph of modern QED to have discovered a systematic, internally consistant and physically sensible procedure to eliminate these infinities and to obtain unique, finite amplitudes. This procedure is called renormalisation.

Renormalised QED has known nothing but success. Some of the processes have been evaluated to the 6th (and partially even to the 8th) order, involving the evaluation of hundreds of diagrams and the most recent major "theoretical" advance in the field is the devising of large computer codes for the algebraic and analytic (not merely numerical) evaluation of diagrams. Experimental ingenuity has kept up with these advances and has shown that all theoretical results are fully borne out.

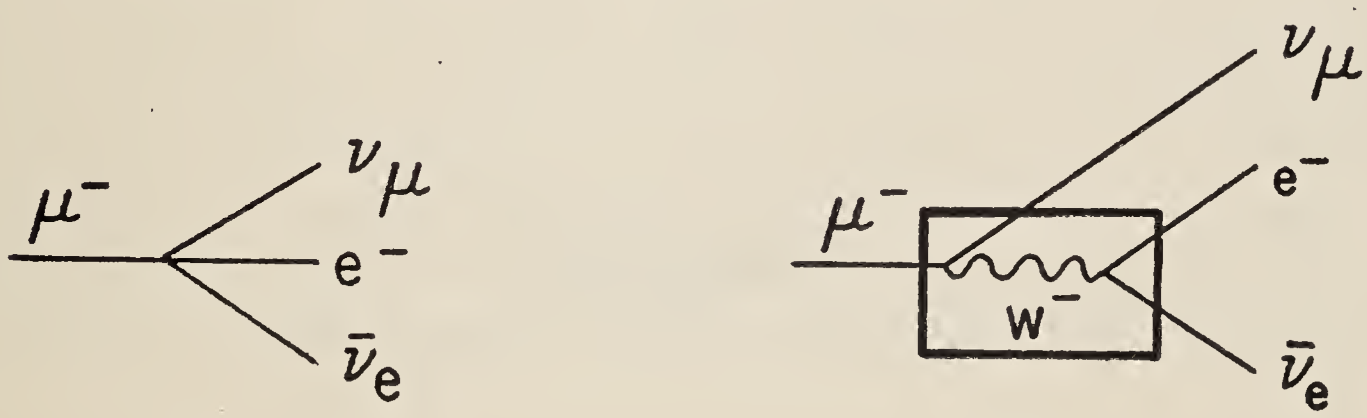
All of this discussion remains valid for the electromagnetic interactions of muons except for the allowance to be made for its higher mass. And again theory and experiment are in marvellous accord. It is obvious that the QED of e's and μ's can be discussed simultaneously. Figure 1b also gives the lowest order diagram describing the scattering $e\,\bar{e} \rightarrow \mu\,\bar{\mu}_u$.

B. Weak

Even though the first known weak process is nuclear β-decay, the decay of the muon, $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$, is the simplest manifestation of the weak interaction, since it involves (unlike β-decay) only leptons. Since there exists no long range weak potential, the weak interaction cannot be mediated by a massless particle. In fact the range of the weak force is very small and, experimentally, might even be zero. If the latter were the case, μ-decay is itself a *primary* weak vertex as shown in figure 2a. The diagram has no internal lines and the electron and the neutrinos are created at the same point at which the muon is destroyed.

This was precisely the picture adopted by Fermi when he wrote down the Hamiltonian for neutron β-decay, $n \rightarrow p + e^- + \bar{\nu}_e$; because of the separate conservation of baryons and leptons, it is natural, as Fermi did, to group the n and p field operators together to form a current and similarly to form another current from the e and ν_e field operators, exactly as the electron and positron operators together form the electromagnetic current. In the case of μ-decay, the conservation of N_μ persuades us to form a muonic current (out of μ and ν_μ) and to let it interact at a point with the electronic current. The picture thus obtained corresponds to the current-current or 4-fermion theory of weak interactions. The space-time transformation property of these weak currents is known from about the mid fifties (Sudarshan and Marshak; Feynman and Gell-Mann) to be that of a combination of vector (as for the electromagnetic current) and axial vector, thus describing the then recently discovered violation of parity symmetry in weak interactions in an economic and elegant way.

After our earlier discussion of QED, the first question that arises now is whether such a theory is renormalisable—*i.e.*, whether here again it is possible to find a redefinition of the fundamental parameters in the theory in such a way as to guarantee finite amplitudes for arbitrarily complex diagrams. The answer is that no one has as yet achieved this. This lack of an essential feature of a good theory, in spite of a successful account of all lowest order processes (I ought to mention here that the weak coupling constant is even smaller than the electromagnetic) was one of the first incentives for the introduction of the weak vector bosons (W-bosons), in analogy with the photon in QED, but this time very massive for obvious reasons. The current-current interaction is then not at a point but has a very short range (figure 2b), and the range can be made small enough not to spoil the successes of the 4-fermion picture. It so happens that the theory is still not renormalisable, though the divergence difficulties are somewhat mitigated.



(a) (b)

Figure 2. μ—decay, a) in the 4-fermion picture and b) in the *W-b*oson picture

This is where the subject stood around 1970. Since then there have been dramatic theoretical developments which I shall discuss presently.

3. Semileptonic interactions

By this is meant processes in which both leptons and hadrons participate.

In low energy processes, both electromagnetic and weak, the distinction between leptons and hadrons is a hard one to see. Thus if the μ^+ were as massive as the proton and were to replace it in the hydrogen atom, the gross features of H-spectroscopy will remain unchanged. Similarly, neutron β–decay characteristics are all but insensitive to the hadronic nature of n and p. But as the energy increases, the specifically hadronic structure becomes more and more apparent through the well-known quantum mechanical duality between distances and momenta (large distances $\sim$ small momenta, and vice versa). In purely leptonic process these higher order structure effects are far less prominent because of the smallness of the leptonic interactions. Form factors and structure functions which describe these effects and which are functions of the available kinematical variables in a given process are an important key to the study of hadrons.

A. Electromagnetic

For a variety of reasons, electromagnetic decays of hadrons are rather rare in general and decays into leptons rarer still. Thus virtually all we know about semileptonic electromagnetic interactions is derived from scattering experiments, e.g., Compton scattering: $\gamma+p\rightarrow\gamma+p$. In contrast to electron Compton scattering (figure 3a), where the only possible internal line in the

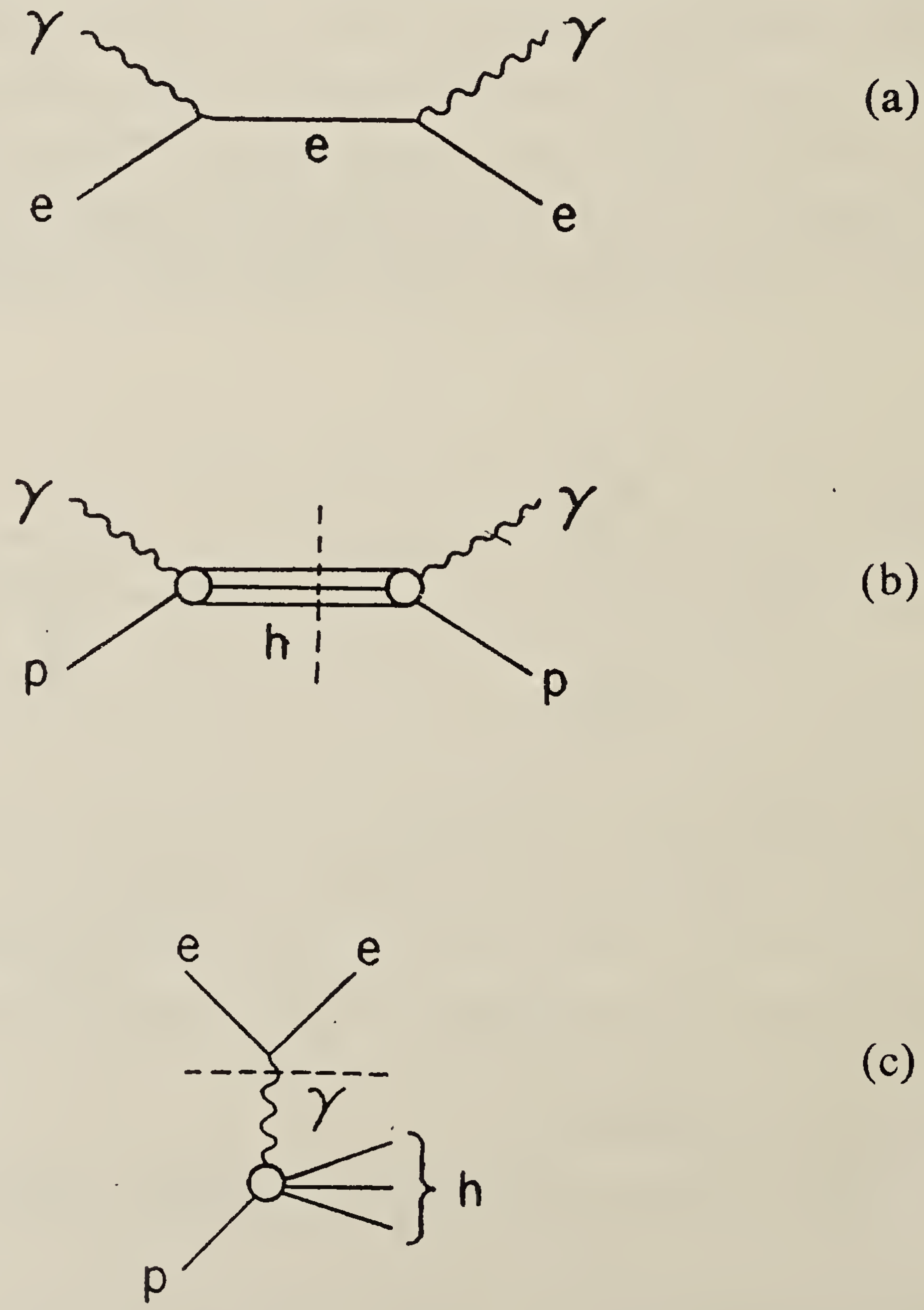


Figure 3. a) Electron Compton scattering; b) proton Compton scattering; c) inelastic ep scattering. The identity of the lower part of c) with either half of b) (as marked by the dashed line) is to be noted

lowest order is an electron, the corresponding diagram (figure 3b) for protons is much richer, with h standing for any set of hadrons compatible with the relevant selection rules (thus illustrating the remarks in the previous paragraph). For these reasons, it is impossible, in the absence of a *non-perturbative* dynamical theory, to "calculate" the vertices in figure 3b.

This remark becomes even more true when the photon is virtual as in figure 3c. This diagram represents the reaction $e+p \rightarrow e+h$, where h is any set of hadrons compatible with selection rules. When the cross-section for this diagram is summed over h (which is experimentally and theoretically a convenience) we obtain the cross-section for the process in which an initial electron scatters into a final electron (with a given momentum) not caring what has become of the initial proton. Quantities pertaining to such processes are called inclusive.

Inclusive electron scattering off protons has become in recent years the main source of our understanding of the hadronic electromagnetic current. The inclusive cross-section (suitably defined) depends in general (*i. e.* without reference to the dynamics) on two kinematic quantities which are conventionally chosen to be the energy difference of the electron (ν) and the (mass)^2 of the photon (Q^2), and particular assumptions about the structure of hadrons lead to particular simple dependences of the observables on ν and Q^2. Experimentally, what is seen is that when both ν and Q^2 are large, the cross-section "scales": the value of a dimensionless ratio of ν and Q^2 determines the value of the cross-section. This observation is the expected one if the proton is assumed to consist of more elementary constituents (called partons) which are charged, but have no electromagnetic structure themselves. It is tempting to identify the partons with quarks and antiquarks, an identification which is on the whole successful. In fact, scaling of the type described above is a major reason for the widespread faith in the notion of quarks.

The other experimental quantity of immediate relevance to this question is the cross-section for the production of hadrons in $e\bar{e}$ collisions (figure 4).

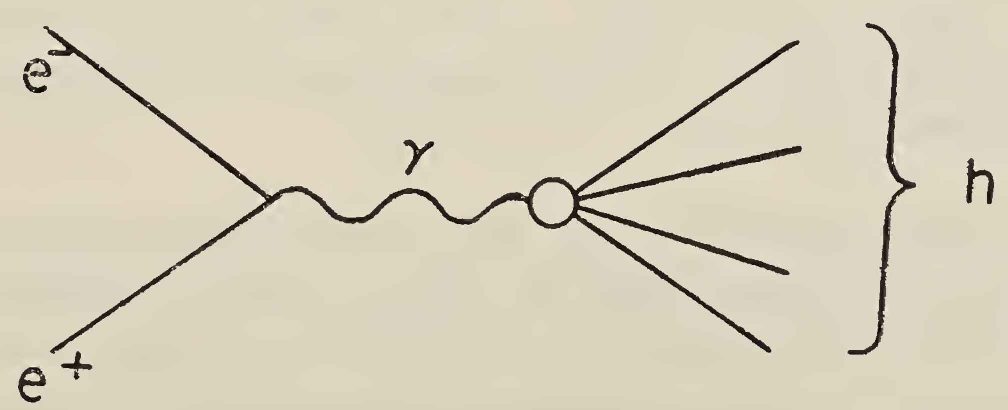


Figure 4. Electron-positron annihilation into hadrons

With the advent of powerful new electron positron storage rings such as SPEAR at Stanford and DORIS at Hamburg, this cross-section, $\sigma(e\,\bar{e}\rightarrow h)$, is now known to a total energy of approximately 7 GeV. Apart from playing the dominant role in the study of the "new hadrons" of the previous talk, this quantity or rather the ratio $R=\sigma(e\,\bar{e}\rightarrow h)/\sigma(e\,\bar{e}\rightarrow\mu\,\bar{\mu})$ is a fundamental signature of the electric charges of the quark-partons. As an example, for asymptotically high energies, R is predicted to have a value of $3\frac{1}{3}$ in the currently fashionable "charm" scheme (see Prof. Pandit's lecture), while experimentally it is about 5.5 at the highest energy and showing no sign of coming down.

As though to reinforce this warning, measurements of inclusive muon scattering off protons over the last two years show signs of a small but clear deviation from scaling. Since the values of ν and q^2 at which this happens are much higher than those at which scaling was seen to hold, we have to say *either* that scaling is a good concept to describe intermediate energy phenomena but becomes progressively inapplicable as the energies increase *or* that the validity of scaling at the lower energies is fortuitous—the truly asymptotic domain is beyond the reach of the present day machines. This latter explanation is clearly not very satisfying (it is perhaps more applicable to the behaviour of R). In any case, the first results from the next generation of electron accelerators are going to be of tremendous interest.

The conclusion to be drawn from all this is that we are still not quite sure of how to account for all observed features of the hadronic electromagnetic current. I may mention in passing that, in the paracharge scheme of which you heard in the previous talk, this current is rather unconventional and the type of deviant behaviour I have mentioned above is not an embarrassment.

B. Weak

There are (as yet!) no experiments on neutrino-antineutrino collisions. But experiments on inclusive ν–p collisions can and have been done, with results (much less precise) more or less conforming to those of the Stanford e–p scattering experiments. Within the limitations imposed by the difficulty of doing neutrino experiments, scaling holds.

Much of the information we have on the basic rules governing semileptonic weak processes is derived from a study of decays (non-leptonic decays which form a substantial fraction of all decays are not explicitly considered here). A typical example is the decay of the pion: $\pi^-\rightarrow\mu^-+\bar{\nu}_\mu$ (or $e^-+\bar{\nu}_e$). Adopting the picture that mesons are bound states of a quark and an antiquark, the diagram for the decay is as shown in figure 5a in the current-current description—the quark current interacts with the lepton current—or as in figure 5b in the W-boson description. The analogy with the corresponding μ–decay diagrams (figure 2) is obvious. (To emphasise the lack of direct experimental evidence for quarks and W-bosons, I have put the conjectural parts of these figures in a black box). From my earlier remarks on electromagnetic form factors, it will also be obvious that the (weak) $q\,\bar{q}\,W$ vertex in figure 5b will be modified by strong interactions and an important success of the theory is to have been able to calculate the "renormalisations" of the basic weak coupling constants induced by the strong interactions.

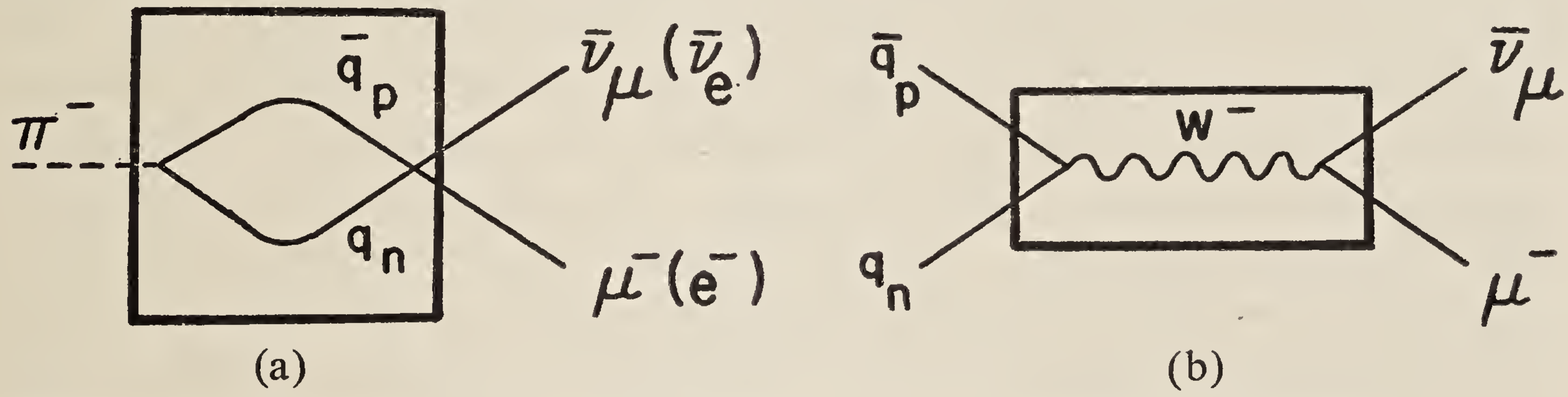


Figure 5. π-decay, a) in the quark picture and b) in the quark and W-boson picture

Apart from such quasi-dynamical results, two striking facts emerge from the study of weak decays:

1) A number of conservation laws applicable to strong and electromagnetic interactions are violated by weak interactions: isospin, strangeness, parity (P), charge conjugation (C) and time-reversal (T) (or equivalently the product of C and P, on account of the TCP theorem which says that in any "reasonable" theory, PCT is always a good selection rule). Of these, isospin is the only symmetry which is bad also for the electromagnetic interaction. Nevertheless, weak interactions continue to respect the conservation of the baryon number N_b, lepton number N_l, muon number N_μ and of course the electric charge Q (not to mention the relativistic conservation laws). Most of these symmetry violations are themselves subject to what may be called secondary selection rules, e.g., there are no decays known in which strangeness changes by more than one unit. These systematics impose as stringent constraints on theories of weak interactions, as do the symmetry violations themselves.

2) Electromagnetism has the striking feature that the basic unit of charge is the same for leptons and hadrons. Strictly speaking, this is perhaps a misleading way of stating the property known as the universality of electromagnetic couplings. The feature I wish to emphasize is not so much the quantisation of charge in units of the electron charge (ignoring the possibility

of real quarks) but the fact that the extra attributes possessed by hadrons do not make for any "renormalisation" of their charge. This property is intimately related to the gauge-invariance of all electromagnetic interactions and more specifically to the conservation of the electromagnetic current.

When we look at weak processes from this viewpoint, the situation appears to be much less simple. There is a vestigial universality of the type mentioned above in that the vector coupling constants governing leptonic (μ-decay) and semileptonic (as seen in the β-decay of the nucleus ^{14}O) processes are the same. Leaving aside the small (and calculable) renormalisation of the corresponding axial vector coupling constant, there seem to be a large number of suppression mechanisms operating, of which the best documented is called Cabibbo suppression: the coupling strength for processes in which strangeness changes is systematically about a quarter of the Fermi coupling for processes in which strangeness does not change, for both vector and axial vector transitions. It is thus natural to start wondering whether we ought not to attempt to formulate gauge principles for weak interactions and at the same time to suspect that any weak gauge symmetry is likely to be a lot less straightforward than in the electromagnetic case.

C. Neutral currents

A quick glance at our discussion so far of the weak interactions (or at the corresponding Feynman diagrams) will show that the currents involved in all of them carry one unit of electric charge (unlike the electromagnetic current). Is it a general property of all weak interactions ? In other words, are there neutral W-bosons? It so happens that there are no strangeness-preserving decays in which the presence of a neutral *weak* current can be easily seen (both the π° and the η mesons decay electromagnetically, denying such a current an opportunity to manifest itself). This disadvantage is absent for some strange particles: the decays $K^{\circ}\rightarrow l\,\bar{l}$ and $K^{+}\rightarrow\pi^{+}l\,\bar{l}$, for example, will be mediated by a neutral W-boson generically denoted W°, (see figure 6 for

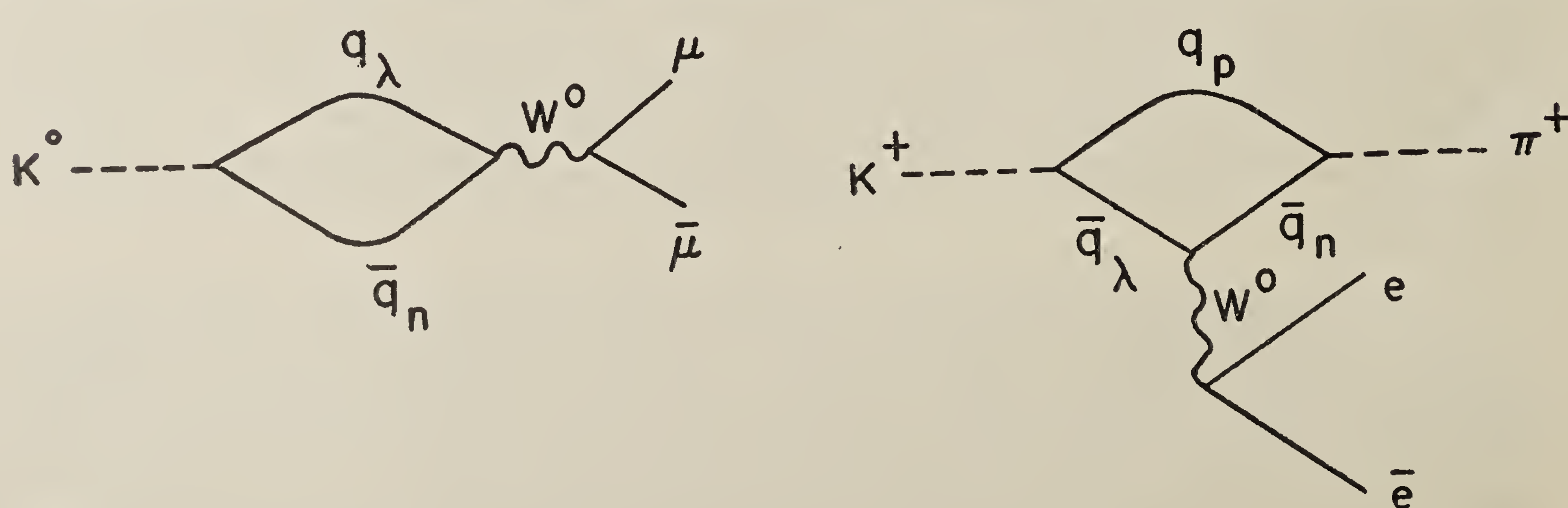


Figure 6. Decays induced by neutral currents : a) $K^{\circ}\rightarrow\mu\bar{\mu}$, b) $K^{+}\rightarrow\pi^{+}e\,\bar{e}$

the relevant diagrams in the quark picture) if it exists. Till very recently experimental searches for such decays yielded negative results (the suppression being much greater than the Cabibbo suppression), leading to the general feeling that there were no W°-bosons in nature. Remembering that the Cabibbo suppression has been known for about 15 years, it may now appear to us that such a conclusion was rather rash. This prejudice thus served to increase the dramatic impact of the discovery in 1972, in inclusive neutrino-scattering experiments off nucleons in the form of nuclei, of events in which no charged lepton was present in the final state. Accepting lepton conservation, we are forced to the conclusion that the final lepton is also a neutrino and that the process is W°-mediated (figure 7).

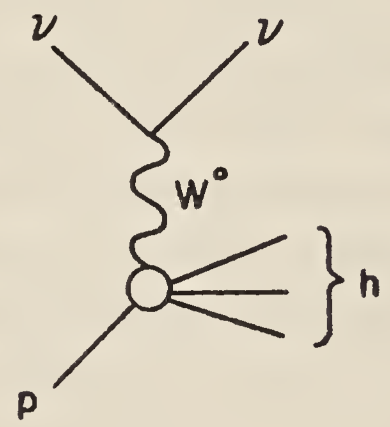


Figure 7. Inelastic νp scattering induced by neutral currents.

The main features of these processes, as known up to now are : 1) both ν_{μ} and $\bar{\nu}_{\mu}$ have this property (whether it is shared also by ν_e and $\bar{\nu}_e$ is not known); 2) leptonic neutral currents couple to one another—examples of the scattering $\bar{\nu}_{\mu} e \to \bar{\nu}_{\mu} e$ which is forbidden for charged N_{μ} conserving currents, are known; 3) the strength of the $\Delta S = 0$ coupling is roughly comparable to that of the Fermi coupling. In spite of the frantic tempo of work of present day particle-physics research, many other questions still remain unanswered, among which the most important is the space-time transformation property—whether the neutral currents are also mixtures of vector and axial vector.

But one question has been answered recently: while both the processes $K^{\circ} \to \mu \bar{\mu}$ and $K^{+} \to \pi^{+} e \bar{e}$ have been seen experimentally, they are suppressed so strongly as to be entirely consistent with the absence of a coupling of $\Delta S \neq 0$ currents with a W°-boson (higher order corrections are then invoked to account for the small but non-vanishing rate).

4. New developments in theory

Clearly, from all this, the theoretical situation in weak interactions is far less satisfactory than in the electromagnetic case. On the other hand, even though more experimental information will be welcome, especially about the neutral currents, a sufficiently extensive body of data exists to act as guidelines in the making of theories.

A. *Universality in weak interactions*

From the vantage point of our present understanding of the subject, the most important of the experimantal facts, for this purpose, is the whole hierarchy of values taken by the effective Fermi coupling constants in different weak processes, mentioned at the end of section 3C. This universality and its apparent violation in a series of steps are a persuasive reason to try and understand weak processes as arising from some kind of gauge principle or principles, but in a more complicated way than in the case of electromagnetism. Part of this complexity lies in the need to reconcile the desired property of gauge invariance with the observed short range of weak interactions. Without, for the moment, addressing this all important question, it can be said immediately that, in a gauge approach, the production of real W-bosons is inescapable given the right kinematic conditions. Secondly, since the number of distinct W-bosons required is at least three, and since in general this number is equal to the number of generators of the group which is "gauged", the gauge group $\mathcal{G}$ has to be bigger than the U (1) of electrodynamics with its one photon. If $\mathcal{G}$ is a simple group, universality *at the primary level* is assured: there is a universal constant g which describes the coupling of any one of the W-bosons to the appropriate current. Now, at energies much lower than required to produce a real W, the effective 4-fermion coupling constant is given by $G_F^i = g^2/\,(m_{W^i})^2$ where i differentiates among the different W's with possibly different masses. The equality of the (vector) couplings in μ-decay and ^{14}O decay is then because, in both, the same (charged) W is exchanged. It is thus possible to make a case in favour of the idea that the various suppression mechanisms (perhaps even extending the meaning of this phrase to include apparent conservation laws, e.g., N_μ) in weak interactions are merely reflections of a non-degenerate mass spectrum for the W-bosons. I must hasten to add that in spite of the appeal of this notion, it is not a universally endorsed one—certainly, there is no candidate as yet for a theory with this ambitious aim.

B. *Spontaneously broken gauge symmetry*

But before becoming so ambitious, we have to face the first problem, the one mentioned before: how to reconcile the zero mass of the gauge bosons with the very short range of the weak interactions. The first theoretical breakthrough which contributed to the resolution of this difficulty came from the study of what are called spontaneously broken symmetries (Nambu, Goldstone, . . .) It was recognised that it is possible to describe a system by dynamical equations (the field equations) or, equivalently, the Lagrangian function from which these equations are derived which have a given symmetry, and still have the states of the theory not manifesting the full symmetry enjoyed by the equations. In such a situation, the ground state of the system (the vacuum) is non-invariant under the symmetry and there are fields whose average (expectation) values in the vacuum are not zero as is the case in more familiar theories. It is an (apparently general) theorem (the Goldstone theorem) that this phenomenon can only occur if the set of fields under discussion includes at least one of vanishing mass and vanishing spin, the so-called Nambu-Goldstone boson.

On the face of it, spontaneously broken symmetries would appear to have little to do with the question we are discussing—if anything the presence of yet another massless particle would seem to make the difficulties even more serious. But the exciting fact is that if the symmetry broken in the Nambu-Goldstone way is a *gauge* symmetry the two zero mass problems (that of the gauge bosons and of the vacuum bosons) disappear together (Higgs, Kibble, . . .). The aim of giving masses to the gauge bosons without giving up the desirable consequences of gauge invariance, especially the conservation of the currents, is thus attained at one stroke, at the cost of introducing a number of *massive* scalar bosons. Some of these Higgs bosons will have to have a non-zero vacuum expectation value. In fact a judicious choice of the Higgs fields and their vacuum-expectation values enables us to approach a variety of desirable goals in a natural way: a) we can arrange for suitable subgroups of the gauge group to remain intact while spontaneously breaking the residual generators, a fact of paramount importance if we wish to discuss the weak and electromagnetic interactions together; b) we can generate a mass spectrum (not just a common mass) for the gauge bosons and so understand the deviations from universality at the 4-fermion level; c) by assigning the Higgs fields appropriate transformation properties under the *non-gauge* symmetries of the theory, the pattern of selection rules obeyed and violated by weak interactions can be made to emerge "spontaneously".

Finally, the answer to our old question of the renormalisability of the theory now turns out to be in the affirmative. I have alluded earlier to the fact that the interaction of massive spin-1 fields with spin-$\frac{1}{2}$ fermions is in general unrenormalisable. But the renormalisability or otherwise of a field theory is an exceedingly complex and subtle question. One general guiding principle, which is of relevance to our purpose, is however available: the larger the number of symmetries a theory has, the greater its potential renormalisability. In accordance with this principle, it is the gauge invariance of QED which makes it renormalisable. Thanks to the pioneering work of 't Hooft, we now know that this principle works even when a gauge symmetry is spontaneously broken—the residual symmetry, particularly the conservation of the currents, is sufficient to control the divergences.

We are thus in possession of a general theoretical framework which has the ability to account, in a most natural and elegant way, for the basic qualitative features of weak interactions, viz., the pattern of symmetries (and symmetry breaking) and the hierarchical manifestation of universality. In addition, once the right picture within this overall framework is found, all that need stand between us and an arbitrarily precise calculation of any measurable quantity is the physical labour of computation.

C. Electromagnetism and the Weinberg–Salam Model

In one respect, my discussion above of the renormalisability question is incomplete. Since some of the *W*-bosons carry electric charge, they can emit and absorb virtual photons in weak processes involving them. And since the electromagnetic coupling constant is much larger than the Fermi coupling constant, such higher order electromagnetic corrections can be more important than higher order weak corrections—we have only considered the latter so far. Electromagnetic interactions of charged, massive, spin—1 bosons are, *in general,* not renormalisable. But here again, the extra symmetry that comes into play if we generate *both* weak and electromagnetic forces from a unified gauge group is sufficient to control the divergences. We have thus arrived at the conclusion that if we take renormalisability as an indispensable minimal demand on the correct theory, we must unify the two kinds of interactions of leptons into an organic whole through the choice of an appropriate gauge group.

The general strategy for constructing the "correct" gauge theory of leptonic and lepton-hadron interactions will thus consist not only in choosing an appropriate gauge group (guided by the number of distinct gauge bosons required) and assigning the leptons and quarks to suitable representations of this group, but also in finding the right representation for the Higgs bosons and in deciding which of them have non-zero vacuum expectation values. The most popular model now, indeed the only one generally taken seriously as having a chance of growing into a complete and correct theory, is the Weinberg-Salam model, whose origins go back to the late sixties, well before the full importance of some of the selection rules (e.g., the suppression of strangeness-changing neutral currents) was understood and before the renormalisation of the theory was satisfactorily settled. The gauge group is

SU (2) ⊗ U (1), leading to four gauge bosons. Two of these are charged, massive and mutually conjugate ($W^{\pm}$) and couple to SU(2) currents. They generate the most familiar charge-changing weak interactions. A linear combination of the third SU (2) boson and the U(1) boson is also massive, but neutral (Z°); it is responsible for the neutral current interaction (the model antedates the discovery of neutral currents and contributed in no small measure to the excitement this discovery produced). The other combination remains massless and is identifiable with the photon. The left handed projections of ν_e and e and of ν_μ and μ (if the neutrinos are massless, they may not have a right handed projection) transform as separate doublets under the SU (2) as do the left-handed q_p and the combination $\cos\theta\, q_n + \sin\theta\, q_\lambda$ ($\sin\theta$ is the Cabibbo suppression factor) of left-handed quarks. The bosons $W^{\pm}$ and Z° therefore couple to left-handed lepton and quark currents in a way which guarantees the observed parity violation and Cabibbo universality.

In its original form, the most visible drawback of this model is the presence, at the $\sin\theta$ level, of a neutral strangeness-changing current, a level far above that seen experimentally. It was to avoid this unpleasantness that Glashow, Iliopoulos and Maiani revived the idea of a fourth, charmed quark q_c, which, together with the Cabibbo-orthogonal combination, $-\sin\theta\, q_n+\cos\theta\, q_\lambda$, was assigned to yet another doublet under the SU (2). The resulting neutral current then has no strangeness-changing part and so, in the lowest order, decays such as $K^{\circ}\rightarrow\mu\,\bar{\mu}$ are absent. The simplicity of this way of solving what had appeared to be a difficult problem was so strikingly evident that detailed work had been done on the expected properties of charmed hadrons, well before the discovery of the ψ-particles. There is as yet no unambiguous experimental evidence for charmed particles with the properties required by the scheme of Glashow *et al.* But, on the other hand, nor do we have as yet a plausible, fundamentally different, alternative way of understanding the suppression of neutral strangeness-changing currents.

D. *Towards a complete theory*

How does the generalised Weinberg-Salam model measure up to *the ideal* gauge theory of weak and electromagnetic interactions ?—the ideal being one in which the flexibility and the potential for unification that is inherent in a spontaneously broken gauge theory are used *naturally* to elucidate the main qualitative features of weak interactions, those discussed at length earlier in this section. It is now nearly 10 years since this model was proposed and we have therefore had enough time to appreciate and praise the many beautiful aspects of this theory. This is therefore perhaps a good time to approach the model with a deliberately critical eye and to use this exercise to identify those features of the model which deviate from the perfect theory we would like to have. Weinberg himself has on a number of occasions warned against taking his model as final, by focussing on properties of the model which are phenomenologically and, in his view, aesthetically unappealing.

In the way in which universality and its breakdown (and conservation laws) are accommodated, the model falls far short of the ideal. The *W*–boson masses take two values and they determine the effective strengths of the usual charged-current and the neutral current interactions. The Cabibbo suppression is incorporated from outside and the model itself has nothing to say about where the Cabibbo rotation comes from. The much stronger suppression of neutral strangeness-changing currents comes as the result of a cancellation in the hadronic contribution to the current rather than inherently, from the properties of the gauge group. About this last point, it must be added that the cancellation mechanism of Glashow, Iliopoulos and Maiani is in its own way an economic solution to an otherwise difficult problem. The price to be paid is, apart from the scepticism physicists show for unexplained ("accidental") cancellations, the introduction of a new class of charmed hadrons. In this context, it is easy enough to understand the excitement caused last year by the discovery of the ψ (J) particles, but despite the most vigorous search, there is so far no evidence for the existence of particles carrying charm in purely hadronic processes. (See Professor Pandit's lecture.)

In the matter of the weak selection rules also, the situation is roughly similar. Leaving aside lepton number conservation, we have no idea why the muon number is (approximately?) conserved. The Weinberg-Salam model just doubles the leptons by having two distinct lepton doublets—in other words, it has no answer to the old question "who ordered the muon?" (and, we may add, the muon-neutrino). As another example, the model incorporates parity violation by letting the left handed leptons play a distinguished role and chooses the transformation properties of the right-handed components to make the electromagnetic current a vector and to couple to the electric charge. As for the violation of CP invariance, its incorporation in a gauge context is only now beginning to get some attention. I shall end this paragraph with the qualitative remark that the first requirement for a natural, gauge theoretic explanation of all these phenomena is a larger gauge group than SU (2) ⊗ U (1).

Theoretically the most exciting feature of the Weinberg-Salam proposal is the unification of the weak force with the electromagnetic one in an inextricable manner. This also brings in some problems in its wake. First of all, SU(2) ⊗ U(1) is not a simple group: there are now two dimensionless coupling constants in the theory corresponding to the SU(2) and the U(1) sub-groups. This is a lapse from the ideal universality that will mark a truly unified theory as especially emphasised by Weinberg. One may attempt to remove this arbitrariness by embedding SU(2) $\otimes$ U(1) in a larger *simple* group. Since we have already seen that a larger gauge group is required also to deal with deviations from universality within the realm of weak interactions alone, it is to be hoped that an extension of the gauge group is possible which will achieve both these ends. Attempts in this direction have so far proved to be not notably successful. It is difficult to consider seriously the few attempts made along this line so far: the groups proposed are implausibly large, requiring the violation of conservation laws such as that of baryon number and of lepton number, but still relying on cancellations to account for the more mundane suppressions such as that of the strangeness-changing neutral current.

More practically, unification has consequences which can, in principle, be unpleasant. While the theory is constructed in such a way that the selection rules governing the electromagnetic interaction remain inviolate in the first order, higher order corrections cannot be unambiguously classified as "weak" or "electromagnetic". Consequently, conservation laws which hold, experimentally, in electromagnetic but not in weak processes can theoretically be broken in order α corrections (*i.e.*, corrections have electromagnetic strength but obey weak selection rules). Ways have been devised to bypass these difficulties, but again at the cost of naturalness.

Putting aside other practical difficulties of this kind, I come now to a question of motivation. The unification of weak and electromagnetic phenomena as exemplified by the Weinberg-Salam theory has often enough been compared to Maxwell's unified theory of electricity and magnetism. But the fact that the essential unity of electric and magnetic phenomena was experimentally established, notably by Ampere and Faraday, before Maxwell's field equations were written down (and that Maxwell was directly inspired by these experiments) is not recalled as often. The discovery of the neutral weak current and what is known of its properties is nowhere near as persuasive an argument for the new unification. In fact, any enlargement of the gauge group to accommodate the hierarchical universality of weak interactions will bring in a proliferation of neutral currents—the hard job is to make them conform to experiment.

Thus, the one strong motivation for the new unification is the desire to have a theory which is renormalisable. But, as I have said earlier, the question of renormalisability is such a cunningly subtle one—any number of theories which at first were thought to be not so have later proved to be renormalisable—that it appears to me premature to base a grand unification scheme on such shifting ground. In the final analysis, renormalisability is, after all, a purely technical requirement. (I am not questioning here the need to renormalise, *i.e.*, to redefine the basic parameters of the theory as they get modified by the interaction, but only the imperativeness of doing this in the usual "renormalisation-theoretic" way).

These remarks are not to be interpreted as being inimical to the idea of unification. My point is only that the physical compulsions in favour of unifying all aspects of weak phenomena are much stronger than those in favour of unifying two such apparently disparate forces as the weak and electromagnetic. The search for *the* correct theory should not be unduly hindered by a doctrinaire attachment to an ambiguous principle (renormalisability) whose physical significance is, moreover, at best obscure. If out of all this work a theory emerges that does unify weak and electromagnetic (and strong ?) interactions, that will be triumph indeed.

5. Experimental results of the past year

I have deliberately based my discussion of the theoretical picture that is begining to take shape on what, from now on, may be called the classical experimental facts concerning weak interactions. I close this lecture with a brief account of some remarkable new experimental results pertaining to these interactions that have been emerging over the last year. These results point to qualitatively new aspects of neutrino physics, very probably even to the existence of altogether new particles.

A. Dilepton events

If there is one single experimental facility which is responsible for the present high level of interest in weak phenomena, it is the availability of good high energy beams of neutrinos (and antineutrinos) at a number of accelerators and of large detectors for the study of their interactions. The two outstanding examples are the experiments at CERN in Geneva and the Fermi National Accelerator Laboratory in the US which first found the muonless events signalling the neutral current (s), using a large heavy-liquid bubble chamber (GARGAMELLE) and an even larger arrangement of counters, respectively.

Right in the middle of the excitement caused by the discovery of the ψ (J) particles, the FNAL experiment found that a small fraction of neutrino interactions with nuclei resulted in the emergence of *two* muons (as identified by their very long range) from the interaction vertex (together with hadrons and, presumably, another invisible lepton). More detailed work has revealed the following features of these events: i) both neutrinos and antineutrinos are effective in producing dimuons; ii) the frequency of these events is about 1/100 of the frequenay of the "normal" 1-muon events; iii) the muons are generally of opposite charge, with about a tenth admixture of $\mu^- \mu^-$ (in ν events) and $\mu^+ \mu^+$ (in $\bar{\nu}$ events); iv) the energy of the μ^- is much (a factor of 3 to 8) larger than that of the μ^+ in the $\mu \bar{\mu}$ events produced by ν ; this relation is reversed in the $\bar{\nu}$-induced events.

It is of course possible to obtain two muons from a neutrino interaction from conventional reactions: ν_μ + nucleus$\rightarrow \mu^-$+ hadrons. The hadrons are mostly pions (and some kaons) and one of them can decay into another μ. The experimenters have tried to eliminate such "delayed" dimuons and the relative frequency of$\sim$1/100 quoted above refers to "prompt" dimuons. Since no ordinary hadron has the very short life time required to give rise to prompt dimuons, some entirely new phenomenon is at work here. The favoured explanation is in terms of the production and decay of charmed hadrons, which if they exist, are expected to have a lifetime of $\sim 10^{-12}$ sec; which is prompt enough. It is unlikely that a W-boson is being produced, for reasons too complicated to go into here. Certain simple mechanisms involving the production and (the simplest mode of) decay of a heavy lepton are also ruled out. The charm interpretation also has its own difficulties, the most serious of which remains the extreme shyness of charm in hadronic and electromagnetic processes.

[Since this lecture was given, both CERN and FNAL have discovered events in which the dilepton consists of one muon and one electron. More interestingly, they have found that there are strange particles (K-mesons) in the final state. Since charmed particles are expected to decay dominantly by changing their strangeness by one unit, this lends strength to the charm interpretation. Still more recently, since this lecture was *written*, there are rumours that the average number of kaons in a dileptonic final state is between 2 and 3. If this is true, the only thing that can be said with certainty is that we ought to wait a while before jumping to conclusions !]

B. The Kolar events

The lack of a super-accelerator of the kind used for high energy neutrino experiment in CERN and FNAL has not prevented experimenters in India from doing neutrino experiments—they have been using the entire universe as an accelerator and the earth as both shield and target for this purpose for quite some time. The neutrinos come from cosmic rays, from the decay of energetic hadrons, and by putting particle detectors very deep underground in the mines of the Kolar Gold Field, they make certain that about the only particles that can initiate a reaction are the neutrinos (of both kinds), all others being filtered out by the earth. Not having much control over the "beam", these experiments cannot compete with the machine experiments in their own domain (among other drawbacks, the event rate is very small) but have nevertheless produced some remarkable results over the last decade.

The events in question have come from the TIFR–Osaka collaboration experiments at KGF and have just been published. The detector used is a visual one and is basically an array of a large number of neon tubes each of which fires when a charged particle passes through it. Thus photographs of the detector system allow a reconstruction of the track of charged particles by providing information on which tubes have fired. One can get a fairly good idea of the nature of the particle (muon, electron, hadron) from the characteristics of the tracks such as the length or penetration of the tracks, whether they are accompanied by "showers", etc., and in some cases by their bending in an ambient magnetic field.

The typical "normal" event has one penetrating track, as would be expected from the reaction ν_μ + nucleus $\rightarrow \mu^-$ + hadrons. But what has caused all the excitement are a set of six events which appear to have more than one (2 or occasionally 3) penetrating tracks which appear to meet at a point *not* in the surrounding rock, but in air (figure 8 shows a three track "anomalous" event). Discounting the possibility of a neutrino interaction with an air nucleus, the most plausible interpretation is that a neutrino hit on a rock nucleus produced a particle with a long enough life time for it to have travelled a relatively long distance (there are vertices about a meter away from the rock face) before decaying into the penetrating tracks seen in the detector. A total of six events is of course a small number on which to base strong conclusions, but the experimenters themselves favour the following properties for this hypothetical particle (the Kolaron ?): i) its lifetime is not shorter than about 10^{-9} sec.; ii) its mass is approximately between 2 and 5 GeV; iii) because of the 3-track events, it is most likely charged; iv) there is at least one track in each event of such length as to be consistent only with a muon, among the known particles; the other tracks are not quite so unambiguous, but are also probably muons; v) the cross section for the production of the particle is not very much smaller than that for the conventional 1-muon cross-section. There is also one event (event 6; figure 9) which is most naturally interpreted as the production (in the material of the magnet) and the subsequent decay (at *P*) of the hypothetical charged particle.

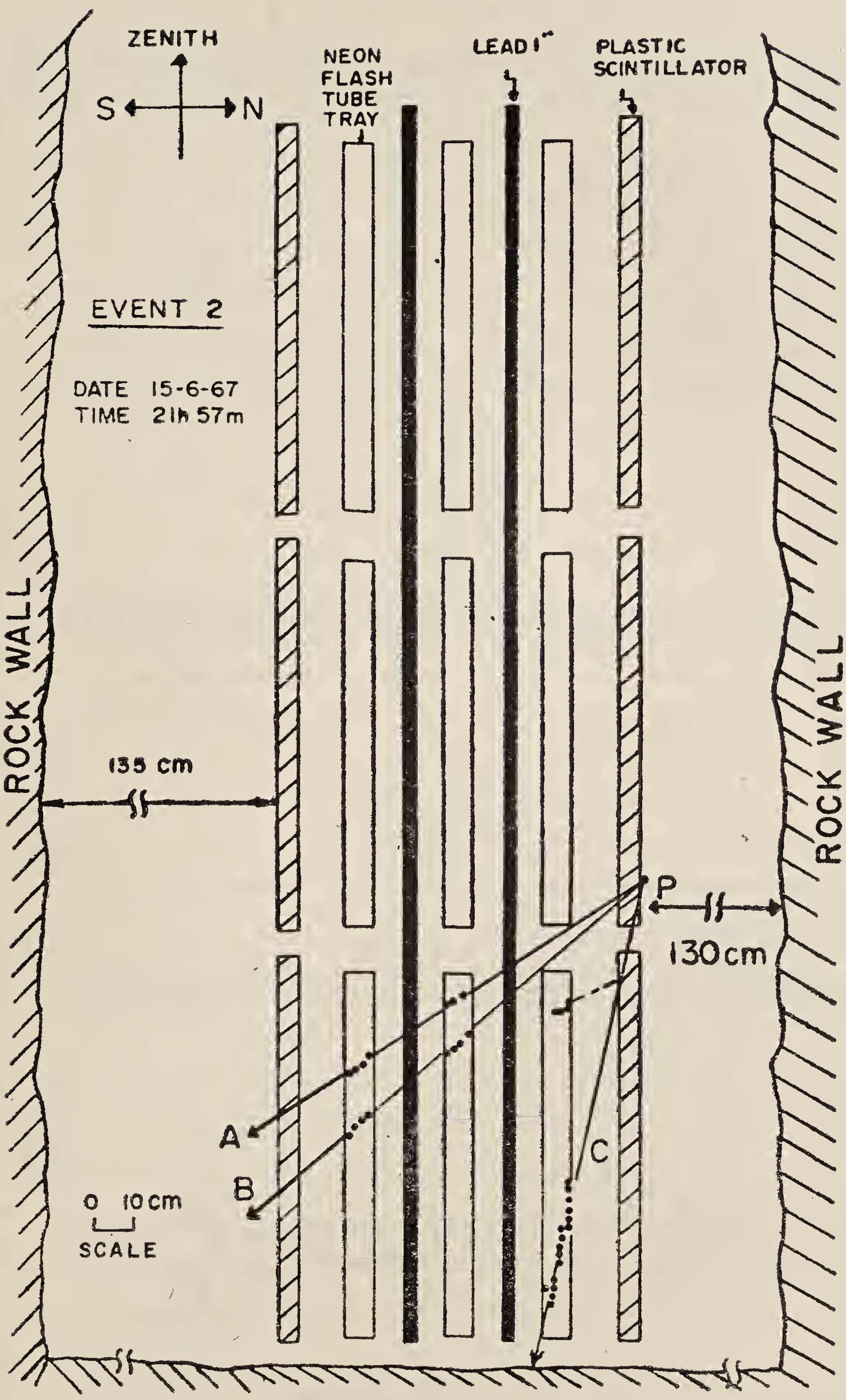


Figure 8. A typical 3-track Kolar event (event 2)

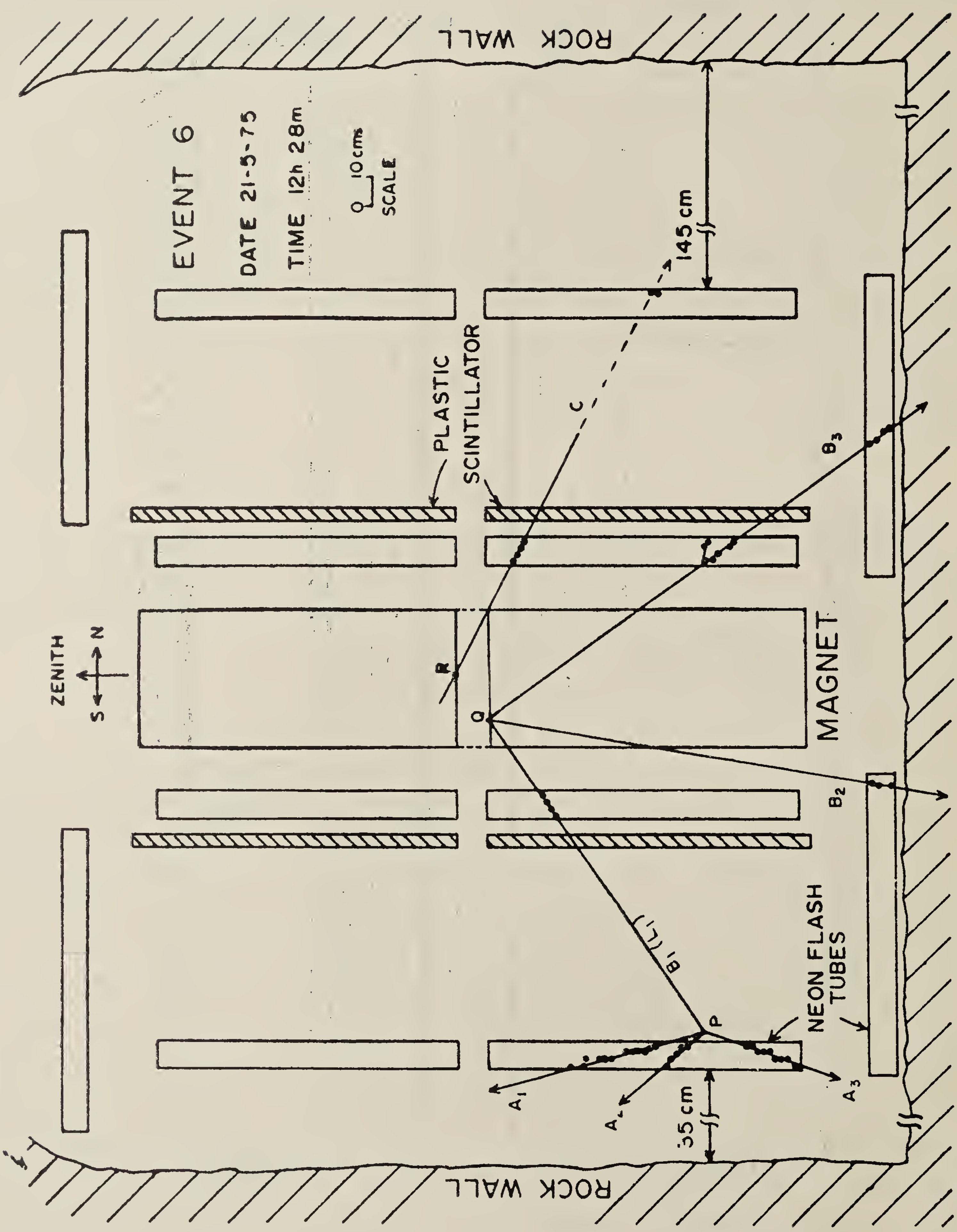


Figure 9. Event 6 from Kolar: the production and decay of the Kolaron?

Theoretically, these trilepton events are even more mystifying than the dilepton events, especially the combination of a large production cross section implying a not too small coupling of the Kolaron to the neutrino, and a long lifetime implying a very small coupling of the Kolaron to its decay products or a very small amount of phase space in the decay. The former alternative will require the production and decay to be mediated by two different types of interactions, with different selection rules and the latter will require that at least one of the decay products is much more massive than a muon. In either case, the conventional pictures of weak interactions (including the generalised Weinberg-Salam model) are incapable of making sense of this phenomenon. Even if one does not accept the interpretative points i) to v) above fully, these pictures are so strikingly different from earlier expectations that this broad conclusion seems to be inescapable. Because of this and because of the extremely slow event rate at Kolar, it is imperative to try and duplicate this experiment at the accelerators. Unfortunately, no corroborating experiment has so far been done—the published claim that the Kolar phenomenon is not seen in accelerator neutrino experiments is based on too many theoretical prejudices to be given any weight.

C. The SLAC events

These events come from the same $e\bar{e}$ colliding facility (SPEAR) at Stanford which has played such a crucial role in the discovery and the elucidation of the properties of the ψ (J) particles. What is observed are reactions of the kind $e+\bar{e}\rightarrow e+\bar{\mu}$ (or $\bar{e}+\mu$) + neutral particles. Extracting information about a rare process like this out of the many other, more profuse, $e\bar{e}$ process is a difficult business and we do not as yet have a very clear picture of the experimental characteristics of these events. A plausible interpretation is in terms of the production, electromagnetically, of a pair of heavy leptons $L^{\pm}$: $e+\bar{e}\rightarrow\gamma$ (virtual) $\rightarrow\bar{L}+L$, followed by the weak decay of L and L : $L^{+}\rightarrow\mu^{+}+\nu_{\mu}+\bar{\nu}$, $L^{-}\rightarrow e^{-}+\bar{\nu}_{e}+\nu$ or vice versa. The proponents of charm also see these as due to the production and subsequent (weak) decay of a pair of charmed hadrons, though, again, the other expected signatures of charm are absent at SPEAR.

Clearly, from all this, the study of the properties of leptons and their interactions is on the threshold of a major revolution. The theoretical progress made in the last decade or so has been dramatically placed in its proper context by these experiments: while reinforcing our faith in the basic guiding principles, these new results clearly point to the need for reassessing the relevance of every element of the theoretical structures we have been putting up. They indicate directions in which generalisations and unifications have to proceed. It will surprise me if a satisfactory theory of the leptonic world has not emerged by the time the Academy organises again a symposium on particle physics.

New hadrons

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1. Introduction

The twelve months just gone by have provided an immensely exciting period in high energy physics. New hadrons were discovered as surprisingly narrow resonances at around 3.1 and 3.7 GeV (about 3.5 and 4 times as massive as the proton) in e^+e^-systems in experiments at Brookhaven and Stanford. An MIT–BNL group (Aubert *et al.* 1974), using 20 GeV protons from the Brookhaven accelerator on a berrylium target, studied the distribution of events of the type $P+P \to e^+ e^- +$ anything (X), as a function of the invariant mass of the produced $e^+ e^-$—system. The result is shown in figure 1. A clear dramatic peak was seen at around 3.1 GeV. Almost immediately followed the experiments of a team of SLAC (Augustin *et al* 1974, Abrams *et al* 1974), who used the SLAC colliding $e^+ e^-$ beam facility (SPEAR) to study the cross-sections for the processes $e^+ e^- \to e^+ e^-$ (Bhabha scattering) $e^+ e^- \to \mu^+ \mu^-$ and $e^+ e^- \to$ hadrons, as a function of the centre of mass energy in very fine steps. The results are shown in figures 2 and 3. These experiments not only observed the sharp peak at 3. 1 GeV, but also discovered a second peak at around 3.7 GeV. We shall refer to these new particles as the ψ (3.1) and the ψ' (3.7), respectively. More detailed experimental studies have established their total decay widths, spins, parities and other properties, indicating that they are vector ($J^P = 1^-$) mesons. In figure 4 their characteristic properties are listed, along with those of the well-known ϱ vector meson for comparison. While the ψ is about 4 times as massive as the ϱ, its decay width is amazingly small being only 4.6 x 10^{-4} times that of the ϱ.

A number of other mesons have also been discovered more recently in the mass range of about 2.8 to 5 GeV.

Discovery of new particle states had become quite common in the preceding couple of decades. Why then all this renewed excitement ? The purpose of my talk is to attempt an answer. For this I shall start by first quickly going over the history of the emergence of some of the main concepts used today for describing hadronic states.

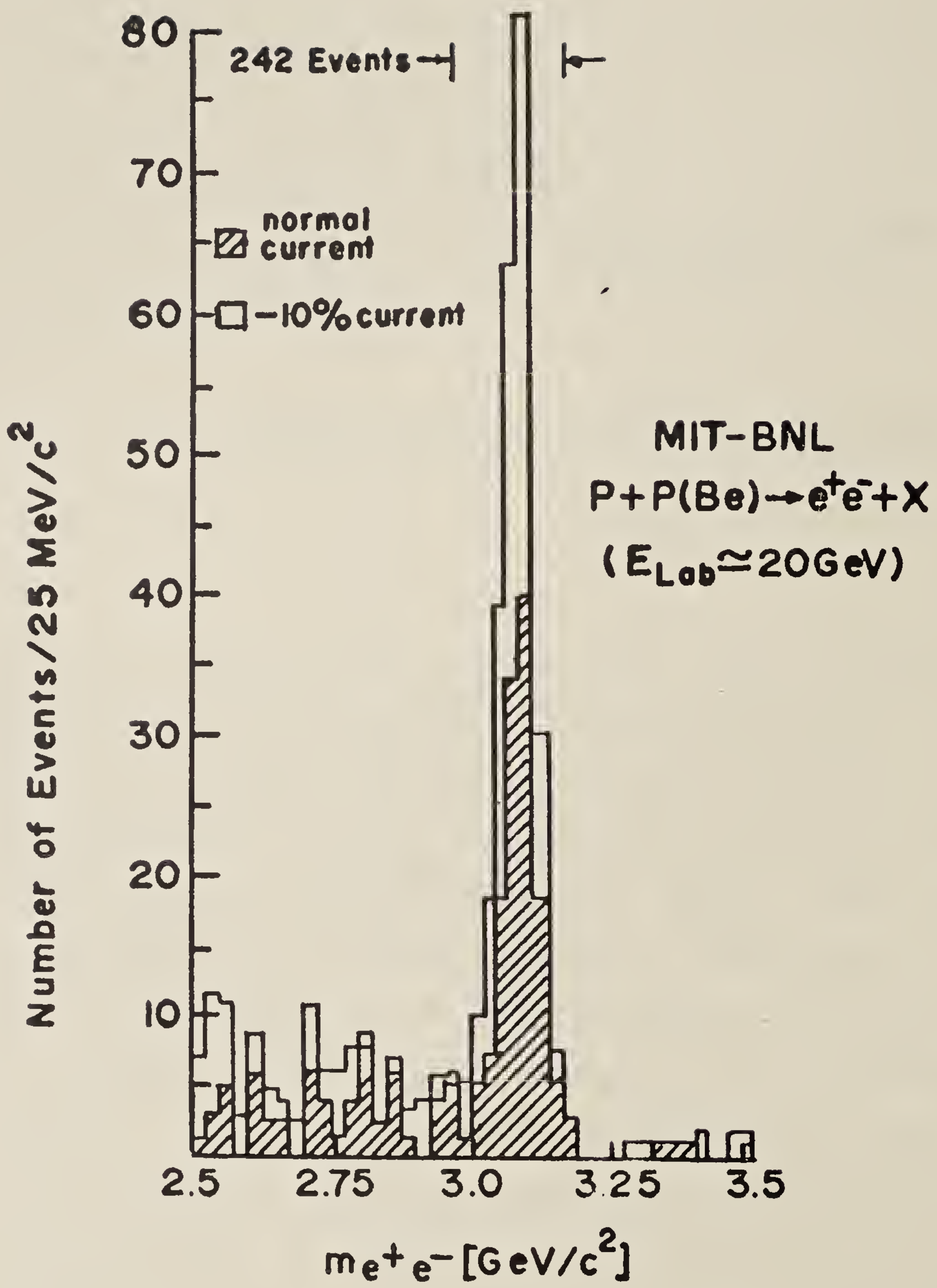


Figure 1. Mass spectrum for events in the mass range $2.5 < m_{ee} < 3.5$ GeV/c^2

2. What are hadrons

To distinguish hadrons from other particles, I have to remind you that in nature we so far know of four categories of interactions. These are : (i) the extremely weak long range *gravitational interaction* responsible for large scale motions of macroscopic bodies; (ii) the long range *electromagnetic interactions* responsible (among other things) for atomic and molecular phenomena, (iii) the extremely short range *weak interactions* responsible for phenomena such as the β-decay of radioactive nuclei and (iv) the short range *strong interatcions*, an example of which is the force binding neutrons and protons in atomic nuclei. For phenomenological purposes of particle physics we can completely neglect the gravitational interaction.

Now we can define *hadrons* to be those particles that take part in strong interactions. Other types of particles: the leptons and the photon do not exhibit strong interactions. Hadrons, of course, do participate also in the other types of interactions.

Hadrons are further subdivided into two classes of particles: (i) the *baryons* and (ii) the *mesons*. Baryons are *fermions,* obeying Fermi-statistics

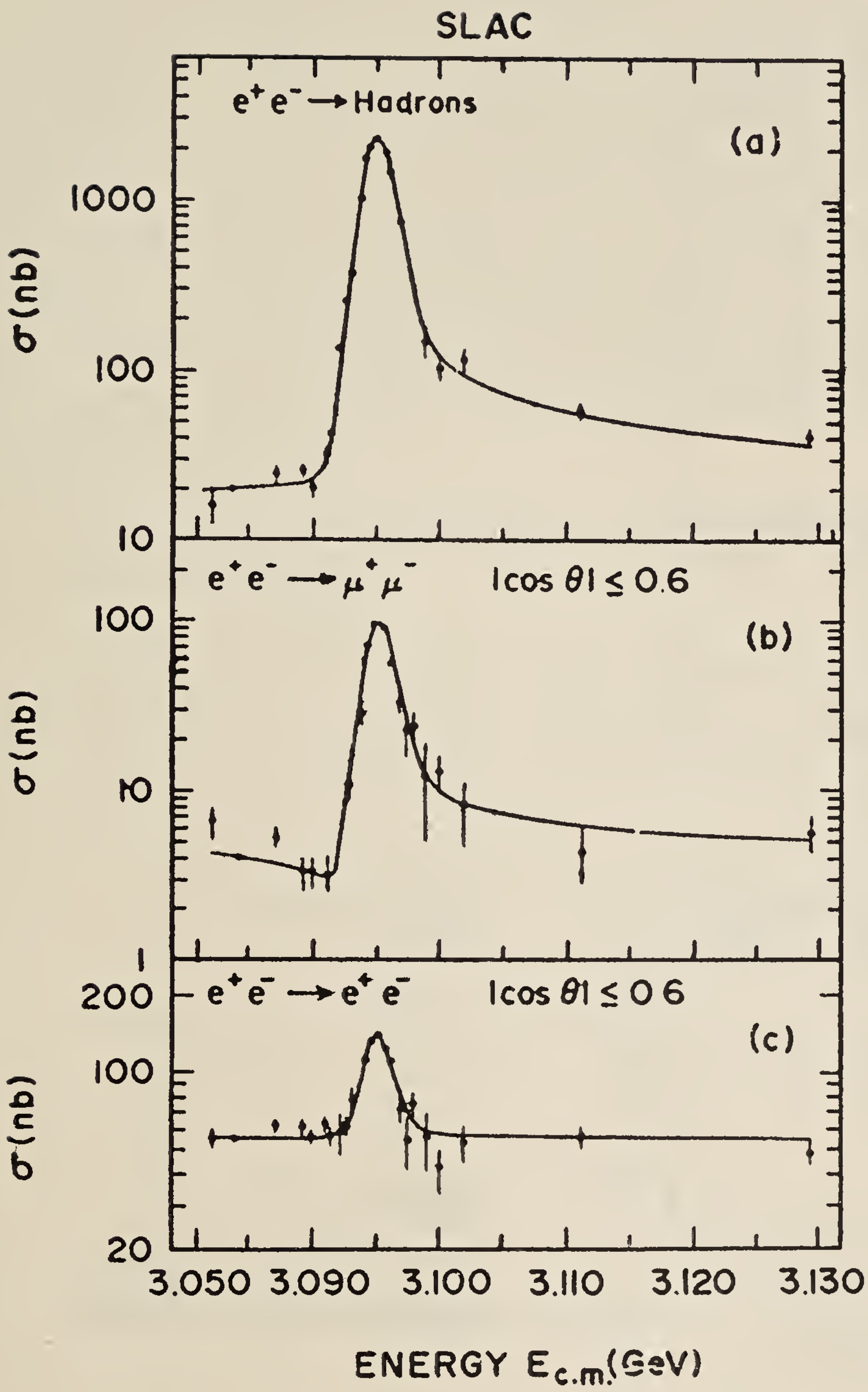


Figure 2.
Cross sections in the region of the ψ (3095)

and possessing half-odd-integral spins. Mesons, on the other hand, are *bosons*, obeying Bose-statistics and possessing integral spins. The neutron (N) and the proton (P) are examples of baryons. An example of mesons is provided by the π-mesons (the pions), postulated by Yukawa (1935) as the quanta of a field of nuclear force, and discovered in cosmic rays by Powell (1946).

The three decades following the discovery of the pions have produced a bumper crop of hadrons.

3. Classification by symmetry groups

It is most important to note that any study of "hadro-dynamics" is beset with the terrible difficulty that no one yet knows how to carry out detailed dynamical calculations with strong interactions in the necessary framework of relativisitic quantum theory. How then is one to go about studying hadrons? A number of partial stop-gap methods have to be resorted to at present. Probably the most useful attack on the relevant problems concerning hadrons has been from the indirect approach of symmetry groups.

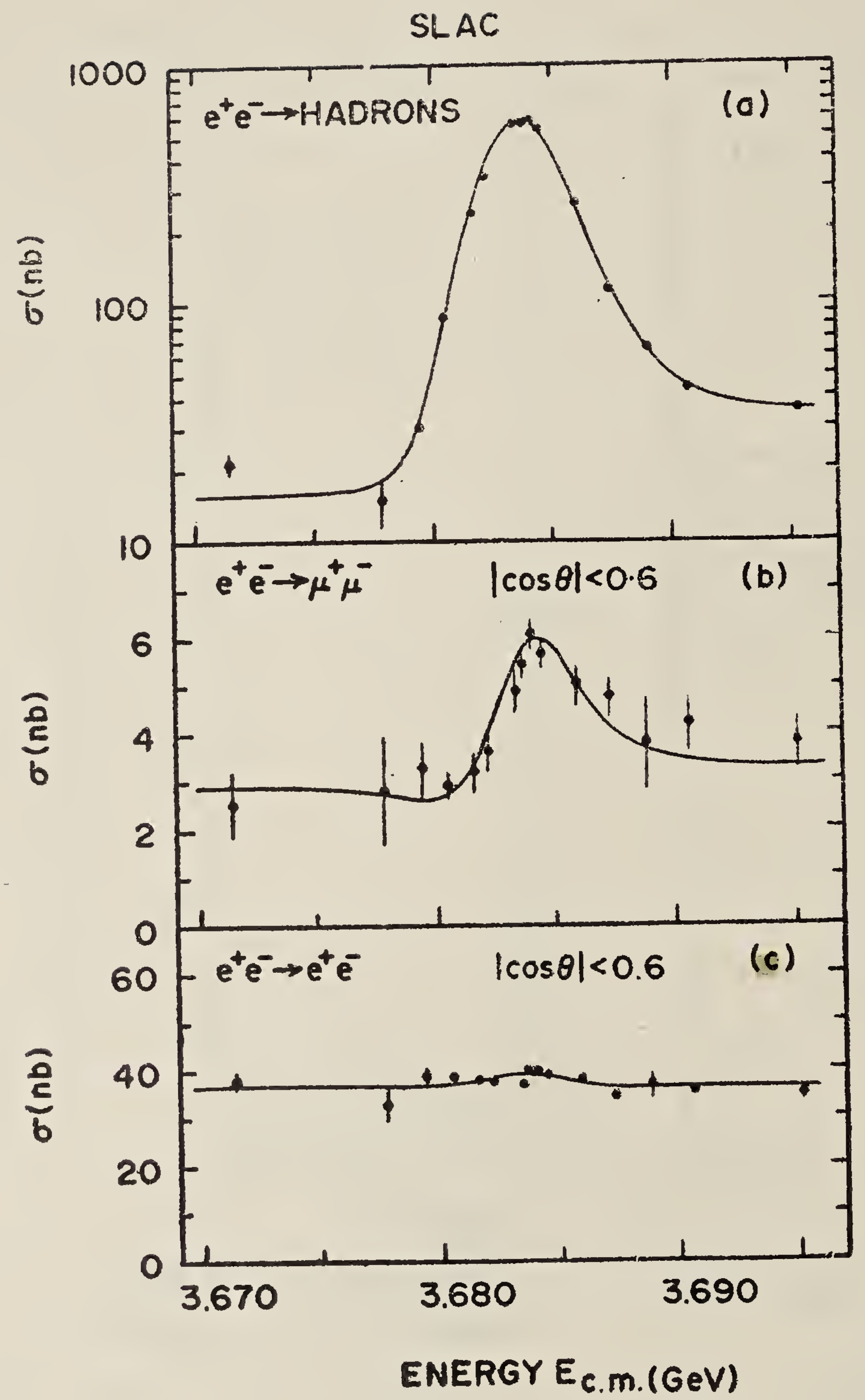


Figure 3. Cross sections in the region of the ψ (3684)

	ψ	ψ'	(Comparison) ρ-meson
Mass(m)	3·095±0·004 GeV	3·684±0·005 GeV	0·77 GeV
Total decay width(Γ)	69±15 keV	225±56 keV	150 MeV
Partial widths $\Gamma(e\bar{e})=\Gamma(\mu\bar{\mu})$	4·8±0·6 keV	2·2±0·3 keV	≃ 7 keV
Spin-parity(J^P)	1^-	1^-	1^-
Charge-conjugation (C)	–	–	–
Baryon number (B)	0	0	0

Note: $\frac{m(\psi)}{m(\rho)} \approx 4$. $\frac{\Gamma(\psi)}{\Gamma(\rho)} \simeq 4{\cdot}6 \times 10^{-4}$

Figure 4. Properties of the ψ (3.1) and the ψ' (3.7)

The basic idea of the symmetry approach is to seek any possible exact or approximate symmetries (other than the space-time symmetries) of the strong interactions. If one succeeds in correctly guessing such a so-called "internal" symmetry group, then at least one can classify the large number of hadrons into families, each member of a particular family being related to other members of that family by transformations of the symmetry group. Interesting characteristic interaction properties of the members of a family would then get related. This would enable us in reducing masses of hadronic data into a great deal of order.

We shall be concerned with the symmetry approach all through the following discussion.

4. Isospin group SU_2 (I), Hypercharge Y and SU_3

Let us look at figure 5. Examples of 8 baryons (with baryon number B=1) and 8 mesons (with B=0), all stable against strong interaction decays,

	Hadron	Mass (MeV)	Q	$I_3(I)$	$Y = 2(Q-I_3)$	$S \equiv (Y-B)$	$SU_2(I)$ dimension	SU_3 dimension
$J^P=\frac{1}{2}^+$	P	938	+1	$+\frac{1}{2}(\frac{1}{2})$	1	0	2	
BARYONS	N	940	0	$-\frac{1}{2}(\frac{1}{2})$	1	0		
	Λ	1116	0	0(0)	0	-1	1	
	Σ^+	1189	+1	+1(1)	0	-1		8
	Σ^0	1192	0	0(1)	0	-1	3	
B=1	Σ^-	1197	-1	-1(1)	0	-1		
	Ξ^0	1315	0	$+\frac{1}{2}(\frac{1}{2})$	-1	-2	2	
	Ξ^-	1321	-1	$-\frac{1}{2}(\frac{1}{2})$	-1	-2		
$J^P=0^-$	π^+	140	+1	+1(1)	0	0		
MESONS	π^0	135	0	0(1)	0	0	3	
	π^-	140	-1	-1(1)	0	0		
	K^+	494	+1	$+\frac{1}{2}(\frac{1}{2})$	1	1		8
B=0	K^0	498	0	$-\frac{1}{2}(\frac{1}{2})$	1	1	2	
	$\bar{K}^0$	498	0	$+\frac{1}{2}(\frac{1}{2})$	-1	-1		
	K^-	494	-1	$-\frac{1}{2}(\frac{1}{2})$	-1	-1	2	
	η	549	0	0(0)	0	0	1	

Note: $Q = I_3 + \frac{Y}{2} = I_3 + \frac{B+S}{2}$ (Gell-Mann-Nishijima Relation)

Figure 5. Example of hadrons

are given here. All the 8 baryons have the same space-time property specified by spin-parity $J^P = (\frac{1}{2})^+$; similarly all the 8 mesons have the same $J^P = 0^-$ (*i.e.*, they are pseudoscalars).

Looking at the column of mass values we notice that these hadrons fall into smaller groups such that members in a particular group have approximately equal masses. Thus we have here examples of what are called *isospin multiplets :* the *singlets* Λ, η ; the *doublets* (P,N), (Ξ^0, Ξ^-), (K^+, K^0), $(\bar{K}^0, K^-)$; and the *triplets* $(\Sigma^+, \Sigma^0, \Sigma^-)$, (π^+, π^0, π^-). The two K-doublets go into each other under the charge-conjugation operation C and must be distinguished. Members within a particular isospin multiplet differ in the value of the electric charge Q (in units of the positron charge). Now the electric charge has to do with the electromagnetic interaction; so if we can ignore this interaction in comparison with the strong interactions, it is possible that the small mass differences within a given isomultiplet may also be ignorable. Members of a given isomultiplet then would appear quite symmetrically in strong interactions. This has led to the recognition that the strong interaction Hamiltonian must be invariant under the operations of the isospin symmetry group SU_2 (I). This group is generated by three hermitean operators I_1, I_2, I_3, satisfying the same commutations relations as the angular momentum operators J_1, J_2, J_3 that generate the group of rotations in ordinary three-dimensional space. The irreducible representations of SU_2 (I) are specified by the dimension of the representation (the family size) $N(I) = (2I+1)$ corresponding to the isospin I of the representing multiplet. Thus we have representations with $I=0$, $I = \frac{1}{2}$, $I=1, \ldots$ corresponding to $N(I) = 1, 2, 3, \ldots$ — the singlets, doublets and triplets, ... referred to earlier. Within a given multiplet with isospin I, one of the three generators, say I_3, can be assigned $(2I+1)$ different values $I_3 = -I, -I+1, \ldots, I$ distinguishing among the members of the family. The column headed I_3 (I) in figure 5 specify these values for the hadrons in question.

Now the members of an isospin multiplet are distinguished both by Q as well as by I_3. Perhaps there is a relation between them ; and if so this relation must be *linear* on account of the additivity of Q as well as of I_3 for a collection of hadrons. It turns out that we can write simply :

$$Q = I_3 + \frac{Y}{2}.$$

The quantity Y is called the '*hypercharge*'. It might appear as if this relation is a trivial definition of Y ; actually, however, Y is independent of I_3 and so as an operator it commutes with all the three generators of SU_2 (I), and this is by no means trivial. Since Q and I_3 are strictly conserved *additive* *quantum numbers* of the strong interactions, we recognize in Y a quantity, independent of the isospin operators, that must be conserved additively in strong interactions. Thus strong interactions are invariant also under the group U_1 (Y) generated by Y. Now the baryon number B is another strictly conserved additive quantum number independent of isospin, so we may introduce the additively conserved combination.

$$S \equiv Y - B,$$

called the *strangeness*. The combination of the above two relations

$$Q = I_3 + \frac{B+S}{2}$$

is the well-known Gell-Mann-Nishijima relation. The nucleons and the pions have $S = O$, *i.e.* they carry no strangeness. Let me remind you that, after the discovery of the π-mesons, the first exciting period in hadron physics occurred in the early 1950's when the strange ($S \neq O$) particles (K, $\bar{K}$, Ω, Σ, Ξ) were discovered. The recognition of the applicability of the isospin symmetry, known earlier in the context of pions and nucleons, also to the strong interactions of these new particles by Gell-Mann and Nishijima was indeed a great step forword in particle physics. It explained the puzzling fact that all these particles were produced through strong interactions while being stable against strong decays into lighter hadrons.

If we look at figure 5 again, we might be led to guess that there may be a yet larger, though a rather approximate, symmetry group of the strong interactions. (The actual search for this group, of course, took many years of imaginative efforts). All the 8 baryons listed, having different I, I_3 and Y values, have masses clustering around the 1 GeV region. Perhaps they may be, as a rough approximation, considered equal, so that all the 8 baryons may be regarded as members of a larger multiplet of a bigger group containing $SU_2(I)$ and $U_1(Y)$. Gell-Mann and Ne'eman proposed in 1961 that the 8 baryons and the 8 pseudoscalar mesons belong to two separate 8-dimensional irreducible representations *(octets)* of the group SU_3, which contains both the isospin as well as the hypercharge operators, I_1, I_2, I_3 and Y, among its eight hermitian generators ($SU_3 \supset SU_2(I) \otimes U_1(Y)$). This scheme has come to be styled as the "Eight-fold Way". This idea had some immediately attractive features: (i) The values of I, I_3 and Y in the SU_3 irreducible representations, are found to come out automatically just the way they were assigned earlier on phenomenological grounds. (ii) If one assumes that the SU_3 symmetry is broken down by a piece in the effective strong interaction Hamiltonian having a simple transformation property under the group, then simple mass-relations can be derived between the masses of the different isomultiplets within an SU_3 family. These mass-formulae turned out to be quite well satisfied by the experimentally measured masses. Such mass relations, in fact, helped in predicting the existence of hadrons that were later discovered experimentally.

The 1960's provided many dramatic confirmations of the approximate SU_3 symmetry scheme as high energy accelerators started producing one after another massive mesonic as well as baryonic resonances. I do not have the time here to describe these discoveries. Let me just tell you that now the list is so long that all practicing particle physicists have to have available specially published long tables of particles and their properties!

As an example, useful for our discussion later on, I list in figure 6 a nonet, i.e., a mixed octet and singlet ($1 \oplus 8$) of SU_3, of vector mesons (ρ, ω, ϕ, K^*, $\bar{K}^*$) with masses in the range of about 800 MeV to about 1 GeV, All these higher mass mesons are allowed to decay strongly by the strong interaction quantum numbers I, I_3, Y into suitable lower mass mesons with widths that range from about 5 MeV to about 150 MeV. It is the largeness of these widths that points to the decays being via strong interactions. The variation in the values of the widths is understandable in terms of the differing phase spaces available for the different decays and the relations of the effective coupling constants can be reasonably understood in terms of the SU_3 symmetry.

5. The SU_3 triplet of quarks

In view of the success of the broken SU_3 symmetry of the strong interactions, and the immense proliferation of the observed hadronic states,

Name	$SU_2(I)$ Multiplet dimension	Y	Mass (MeV)	Decay width (MeV)	Dominant Decay mode
ρ	$\underline{3}$	0	770	150	$\pi\pi$
ω	$\underline{1}$	0	783	10	$\pi^+\pi^-\pi^0$
ϕ	$\underline{1}$	0	1019	4	$K\bar{K}$
K^*	$\underline{2}$	1	892	50	$K\pi$
$\bar{K}^*$	$\underline{2}$	-1	892	50	$\bar{K}\pi$

Figure 6. The ρ - nonet of vector ($J^P = 1^-$) mesons

a proposal for a further simplification of the picture was made in 1964 by Gell-mann and Zweig. They suggested that three fundamental spin ½ fields belonging to the basic (or defining) triplet representation of SU_3, and carrying suitable amounts of all the other remaining quantum numbers (Q, B), be introduced to describe hadronic physics. All the observed hadrons are then to be looked upon as composites of these these three basic fields and their hermitian adjoints. These three fields are called the quark fields and denoted by $q \equiv (p, n, \lambda)$. Their quantum numbers are listed in figure 7A, where I have also indicated, as an illustration, how the internal quantum numbers of the ρ-nonet of vector mesons (of figure 7B) are expressed in terms of the quark-fields. All mesons (B=0) are as $(q\bar{q})$ – states, whereas all baryons (B=1) are (qqq) – states. Even though no quarks have been found (and it could be that they cannot be present in isolated form for some deep reason), this idea has been playing a very important role in hadronic physics. The observed breaking of the SU_3 symmetry down to SU_2 (I) can

(A)

Quark	$I_3(I)$	Q	Y $2(Q-I_3)$	B	S (Y-B)
p	$+\frac{1}{2}(\frac{1}{2})$	$+\frac{2}{3}$	$+\frac{1}{3}$	$\frac{1}{3}$	0
n	$-\frac{1}{2}(\frac{1}{2})$	$-\frac{1}{3}$	$+\frac{1}{3}$	$\frac{1}{3}$	0
λ	0(0)	$-\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{3}$	-1

(B)

Meson name	Quark-composition
ρ^+	$p\bar{n}$
ρ^0	$\frac{1}{\sqrt{2}}(p\bar{p}-n\bar{n})$
ρ^-	$n\bar{p}$
ω	$\frac{1}{\sqrt{2}}(p\bar{p}+n\bar{n})$
ϕ	$\lambda\bar{\lambda}$
K^{*+}	$p\bar{\lambda}$
K^{*0}	$n\bar{\lambda}$
$\bar{K}^{*0}$	$\lambda\bar{n}$
K^{*-}	$\lambda\bar{p}$

Note: Baryons (B=1) are (qqq)-states.

Figure 7. A. The SU_3 - triplet of quarks : $q \equiv (p, n, \lambda)$
B. Example : Expressing the internal quantum numbers of the ρ - nonet of vector mesons in terms of the quarks : $(q\bar{q})$states.

be introduced simply by assuming that the singlet quark λ has a higher mass than the common mass of the doublet (p, n).

6. The ψ-particles

With the background developed so far, we are now in a position to properly appreciate the importance of the discoveries last year of the ψ-particles that I spoke of at the beginning of my talk.

As pointed out right at the start, the ψ-particles are almost certainly vector mesons. But then they must have something entirely new about them. Thus the ψ (3.1) is about 4 times as massive as the ρ vector meson, and so would be expected to decay by the conventional strong interactions with an enormous decay width of the order of a few hundred MeV. Actually its observed width is really very tiny, being only 4.6×10^{-4} times that of the ρ. There must be something that drastically inhibits its decay into the lighter hadrons inspite of the enormous phase space that would be available for such decays.

To incorporate this unexpected situation, it is clear that the so far developed broken SU_3 scheme for hadrons has to be modified without, however, giving up its past successes. A number of theoretical proposals were put forward in response to this situation. Many of these have been eliminated by now by further experiments. Some are still in the field. For the final generally accepted scheme to emerge, it will presumably still take a great deal of detailed experimental work. So the account I give now of such attempts will not have the same established status as of the theory described so far. Let me now persent the outlines of a few of the schemes put forward.

7. The Paracharge (Z) and SU_4 (Z)

The scheme I shall outline first was proposed and developed at TIFR (Das, Divakaran, Pandit and Singh 1975 a&b). The main idea is to introduce a new additive quantum number, called the *Paracharge (Z)*, assumed to be strictly conserved in strong interactions. The ψ-particles are assigned $Z \neq 0$, whereas all the other hadrons have $Z=0$. This ensures, for example, that the ψ (3.1) cannot decay by strong interactions into older ($Z=0$) hadrons, explaining why the width of the ψ is not a large typical strong interaction width.

Having postulated that the strong interactions are invariant under a new symmetry U_1 (Z), this symmetry is combined with the old SU_3 symmetry group into the simplest larger group $SU_4 \supset SU_3 \otimes U_1$ (Z). The SU_3 triplet of quarks

A. The Quark Quartet of $SU_4(Z)$: $\xi \equiv (q, \chi) \equiv (p, n, \lambda, \chi)$

Quark	Z	I_3	Q	Y	B	SU_3-dim
p	0	$+\frac{1}{2}$	$+\frac{2}{3}$	$+\frac{1}{3}$	$\frac{1}{3}$	
n	0	$-\frac{1}{2}$	$-\frac{1}{3}$	$+\frac{1}{3}$	$\frac{1}{3}$	$\underline{3}$
λ	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{3}$	
χ	1	0	$-\frac{1}{3}$	$-\frac{2}{3}$	$\frac{1}{3}$	$\underline{1}$

B. Electric charge $Q = I_3 + \frac{Y}{2}$, (no Z contribution).

C. The $\underline{16}$ plet$(\xi\bar{\xi})$ of vector mesons containing the ρ-nonet:

States		SU_3-repn.	Z
$q\bar{q}$:	$(\rho, \omega, \phi, K^*, \bar{K}^*)$	$\underline{1} \oplus \underline{8}$	0
$q\bar{\chi}$:	(D^+, D^0): $I = \frac{1}{2}$, $Y = 1$ S : $I = Y = 0$	$\underline{3}$	-1
$\chi\bar{q}$:	$(\bar{D}^0, D^-)$: $I = \frac{1}{2}$, $Y = -1$ $\bar{S}$: $I = Y = 0$	$\underline{3}^*$	$+1$
$\chi\bar{\chi}$:	P : $I = Y = 0$	$\underline{1}$	0

Define. $C = \pm$ combination $S^0_\pm \equiv \frac{S \pm \bar{S}}{\sqrt{2}}$. $\psi(3.1) \equiv S^0_-$

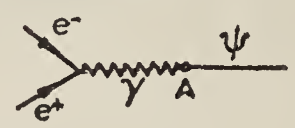
Figure 8. $SU_4(Z)$ scheme with paracharge Z: $SU_4(Z) \supset SU_3 \otimes U_1(Z)$ (Das, Divakaran, Pandit and Singh)

$q = (p, n, \lambda)$ are thus extended to the *basic quartet* $\xi = (p, n, \lambda, \chi)$ of quarks by adjoining a fourth quark χ, which is an SU_3 singlet and carries the new quantum number $Z = 1$ (the older triplet q having $Z = 0$). The quantum numbers of the four quarks of the paracharge-scheme and the construction of the enlarged SU_4 mulitiplet of the vector mesons (containing the ρ) to which the ψ (3.1) is assigned, are displayed in figure 8. The old $\underline{1} \oplus \underline{8}$ mixed nonet representation of SU_3 is now extended to the 16-plet, mixed $\underline{1} \oplus \underline{15}$, representation of SU_4. This means postulating a $Z = -1$ SU_3-triplet $(\sim q\bar{\chi})$ consisting of the isodoublet (D^+, D^0) with $Y = 1$ and an isosinglet S with $Y = 0$, the antiparticles $(\sim \bar{\chi} q)$ of these $\{(\bar{D}^0, D^-), \bar{S}\}$—with $Z = +1$, and an additional SU_3 singlet, the P, with $Z = 0$ $(\sim \chi \bar{\chi})$.

It is assumed that the ψ is produced in e^+e^- annihilation electromagnetically by the process $e^+ e^- \to \gamma \to \psi$ (figure 9a). Since the photon γ has charge-conjugation $C = -$, we identify the $C = -$mixture of the S and $\bar{S}$ with the ψ :

$$\psi\,(3.1) \equiv S_-{}^\circ \equiv \frac{S - \bar{S}}{\sqrt{2}}.$$

A. ψ-production in $e^+ e^-$



New Z-changing Pauli Electromagnetic Interaction at Vertex A:

$$L_{em}(\Delta Z) \sim \frac{\beta e}{2M}\left[\bar{X}\,\sigma_{\mu\nu}\lambda + \bar{\lambda}\,\sigma_{\mu\nu} X\right]F_{\mu\nu}$$

B. $SU_4 \to SU_3$ symmetry breaking($m(X) \gg m(q)$): 16-plet mass formula

$2m^2(\psi) = m^2(\rho) + m^2(P)$

Input: $m(\psi) = 3{\cdot}1$ GeV, $m(\rho) = 0{\cdot}77$ GeV.

Output $m(P) \approx 4{\cdot}3$ GeV. (Prediction)

The P has $I = Y = Z = 0$: Expected to have a large (a few 100 MeV) width.

C. Another 16-plet of vector mesons containing the ρ'(1600 MeV)

$\psi'(3.7) \equiv S_1^{0\,\prime}$

Prediction: P', $m(P') \approx 5$ GeV, Width $\approx$ a few 100 MeVs.

D. The 16-plet of tensor($J^P = 2^+$) mesons containing the A_2-nonet

Predictions (with spin-unitary spin independence): $S_1^0(T)$ at $\approx 3{\cdot}3$ GeV.
P (T) at $\approx 4{\cdot}6$ GeV.

E. The 15-plet of pseudoscalar($J^P = 0^-$) mesons containing the π-octet.

Predictions (with spin-unitary spin independence): $S_1^0(PS)$ at $\approx 2{\cdot}9$ GeV.
P (PS) at $\approx 3{\cdot}5$ GeV.

Figure 9. $SU_4(Z)$ assignments of the new hadrons: Enlargements of all SU_3-multiplets predicted

Clearly, now the photon must be postulated to have a new interaction that is Z-changing ($|\Delta Z| = 1$) to be able to produce the ψ. The new addition to the hadronic electromagnetic current must be chargeless, since we continue to have $Q = I_3 + Y/2$. The new interaction is that of the Pauli type:

$$L_{em}(\Delta Z) \sim \frac{\beta e}{2M}\,[\bar{X}\sigma_{\mu\nu}\lambda + \bar{\lambda}\sigma_{\mu\nu}X]\,F_{\mu\nu},$$

where $F_{\mu\nu}$ is the electromagnetic field tensor and β and M are parameters. This modification of the electromagnetic interaction leaves unchanged the experimentally established conventional electrodynamics of the charged leptons. The modification that *has* been introduced is only in a part of physics which is surely still far from a final definitive stage.

Next we introduce the SU_4 symmetry breaking down to SU_3, assuming the responsible term in the effective Hamiltonian to transform as $\sim \chi\bar{\chi}$, ($q-\chi$ mass-splitting). This leads to the mass relation for the (ideally) mixed 16-plet:

$$2m^2(\psi) = m^2(\varrho) + m^2(\mathrm{P}).$$

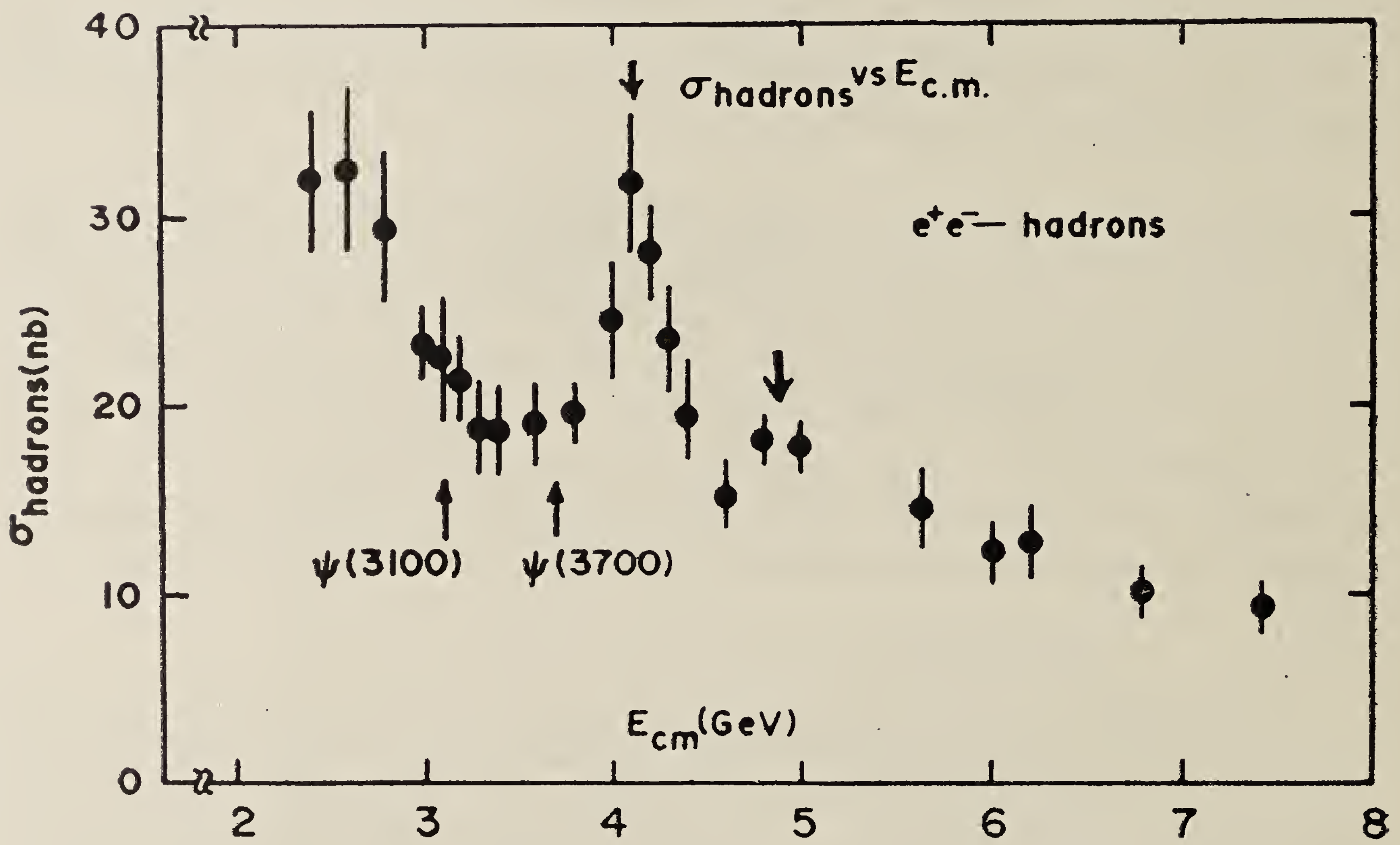
Using $m(\psi) \simeq 3.1$ GeV, $m(\varrho) \simeq 0.77$ GeV, we *predict* the mass of the $\mathrm{P} \approx 4.3$ GeV. The P has $Z=0$ so that it is expected to have a large decay width typical of strong interaction decays.

The ψ' (3.7) is similarly assigned to another 16-plet to which the older vector mesons of the ϱ' (1600 MeV)-family belong. Then the corresponding new $Z=0$ state, the P′, is expected at around ≈ 5 GeV, again with a large width. Since the ψ and the ψ' have the same quantum numbers the decay $\psi' \to \psi + 2\pi$ is possible via strong interactions and is actually observed as the most important decay. The smallness of the width of the ψ' inspite of this possibility, is understood on some other considerations (PCAC for pions) as pointed out in the context of the "Charmonium" model (Pasupathy 1974, 1975).

The existence of the broad vector mesons, the P and the P′ at ≈ 4.3 and 5 GeV were proposed as crucial tests of the scheme. Later experimental measurement (Augustin *et al* 1975, Feldman and Perl 1975) of the cross-section σ ($e^+ e^- \to$ hadrons) at c.m. energies going up to 8 GeV (figure 10) have revealed possible broad resonance structures at $\simeq 4.15$ GeV and $\simeq 4.9$ GeV. This is extremely gratifying for the paracharge scheme.

In this scheme, one also expects enlargements of all the older SU_3 multiplets of mesons and baryons. Thus one expects, e.g., the pseudoscalar mesons (of the $\underline{15}$ plet containing the old π-octet) S^0_+ (PS), P (PS) and the tensor ($J^P = 2^+$) mesons (of the $\underline{16}$-plet containing the old A_2-nonet) S^0_+ (T), P (T). Spin-unitaryspin independence suggests m (S^0_+ (PS)) ≈ 2.9 GeV and m (S^0_+ (T)) ≈ 3.3 GeV; and these further imply by the SU_4 mass-formulae m (P (PS)) ≈ 3.5 GeV and m (P (T)) ≈ 4.6 GeV. With these states we expect the decays: $\psi' \to S^0_+ (\mathrm{T}) + \gamma$, $\mathrm{P(PS)} + \gamma$ and $\psi \to S^0_+ (\mathrm{PS}) + \gamma$. Very recent experiments (SLAC, DESY) (Braunschweig *et al* 1975, Feldman *et al* 1975) have established two mesons at $\simeq 3.41$ GeV and $\simeq 3.53$ GeV in the decays $\psi' \to (3.41) + \gamma$, $\psi' \to (3.53) + \gamma$. The state at 3.53 is broad and does not decay into two pseudoscalar mesons, in agreement with it being identified as the pseudoscalar state P (PS). There have also been reports of the observation (DESY) of the decay $\psi \to (2.8) + \gamma$, where the state at 2.8 can be the S^0_+ (PS). (see figure 10).

A. The P seen at 4.15 GeV. and the P$'$ strongly indicated at $\simeq$ 4.9 GeV. in $e^+e^- \to$ hadrons (SLAC)



B. Other mesons seen in experiments:

$S^0_+(PS)$ at $\simeq$ 2.8 GeV (DESY) : $(\psi \to S^0_+(PS) + \gamma)$
$S^0_+(T)$ at $\simeq$ 3.41 GeV (SLAC) : $(\psi' \to S^0_+(T) + \gamma)$
P(PS) at $\simeq$ 3.53 GeV (SLAC, DESY) : $(\psi' \to P(PS) + \gamma')$
(P(PS) is broad, $\not\to$ 2 psendoscalar mesons).

Figure 10. Experimental verification of $SU_4(Z)$ assignments

More detailed experiments on the different decay modes of the ψ and the ψ' have also been made in the past months. The typical features of the decays can be well understood qualitatively in the paracharge scheme. (Das *et al* 1975c).

Thus the paracharge scheme fares well on all phenomenological considerations so far. Besides a possibly viable theory of weak-interactions (Das *et al* 1975d) has also been constructed by us in the framework of the paracharge scheme.

8. Some other schemes : Charm, Colour

It is not possible in the time available to talk of all the schemes that have been put forward for dealing with the new hadrons. All the same, I do wish to mention, however briefly, two schemes that have been so much talked about in the past year.

The *"charm"* scheme (figure 11) has its genesis in the proposal of Glashow, Illiopoulos and Maiani that a fourth SU_3–singlet quark c, carrying a new additive quantum number—the charm $\mathcal{C}$—be introduced along with the charmless old triplet (p, n, λ) for constructing a gauge theory of weak and electromagnetic interactions free from a strangeness-changing neutral current. On the discovery of the ψ–particles, a number of authors (Gaillard *et al* 1974, Rujula and Glashow 1975, Pasupathy 1974 & 1975) immediately interpreted these new hadrons in an SU_4 ($\mathcal{C}$) framework as vector $c\bar{c}$ states. To account for the suppression of their strong decays into older hadrons they had to

A. The Charmed Quark c.(Glashow, Illiopoulos and Maiani)

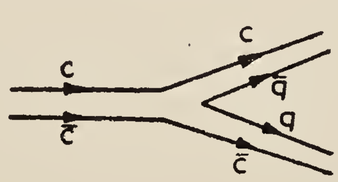
New quantum number $\mathcal{C}$ (charm) $= \begin{cases} 1 \text{ for } c & (\underline{1} \text{ of } SU_3), \\ 0 \text{ for}(p,n,\lambda) & (\underline{3} \text{ of } SU_3). \end{cases}$

The c has $Q=+\frac{2}{3}$, $Y=+\frac{1}{3}$ (same as the p)

$$Q = I_3 + \frac{Y}{2} + \frac{\mathcal{C}}{2}\ .$$

B. All new hadrons are pure $c\bar{c}$ ('charmonium') states (Hidden charm)

(Gaillard, Lee and Rosner, De Rújula and Glashow, Pasupathy,...)
Suppression of strong decays by "Zweig's Rule"



C. SU_4 ($\mathcal{C}$) multiplets containing new "charmed" hadrons predicted.

D. Difficulties: (1) No "charmed" hadrons found in extensive experimental searches in $\approx$ 2-5 GeV region.
(2) The broad resonance at 4·15 GeV (and possibly at 4·9 GeV) in e^+e^- not easy to understand.
(3) The ψ' and the ψ decays into π's, K's expected to be similar. Experiments show them to be different.

Figure 11. The *Charm* scheme

assume that these so-called "charmonium" states are exceptionally pure, having no contamination from other quarks, so that Zweig's rule forbids such decays (assuming any C-carrying hadrons to be sufficiently massive).

In spite of its initial attractiveness, the charm model has run against some difficulties: (i) New charmed hadron states are predicted in SU_4 (C) multiplets, but none have been found in extensive experimental searches. (ii) The broad resonance at 4.15 GeV discovered later in $e^+ e^-$ annihilation is difficult to accommodate in the scheme. (iii) The qualitative features of the decays into π's and K's of the ψ and the ψ' are expected to be similar, but are found experimentally to be quite different.

The *"colour"* scheme makes use of three sets of basic triplets first introduced by Han and Nambu to avoid having to introduce (as in the quark model) basic fields carrying fractional values of the electric charge Q. The strong interaction symmetry group is then taken to be $SU'_3 \otimes SU_3$. The additional three-valued label on which the SU'_3 operates is called the "colour". In this scheme the hadronic electromagnetic current has colour-changing pieces that can produce coloured vector mesons. The ψ–particles are interpreted (Sanda and Terazawa 1975, Feldman and Matthews 1975, Tsai 1975) to be such coloured mesons. The major problem in this scheme is that with 9 basic fields, we expect an $SU'_3 \otimes SU_3$ multiplet of mesons to have $9 \times 9 = 81$ states, and one feels rather uncomfortable introducing such a large number of states when only a few new ones have been found.

As I have stated earlier, the theoretical as well as the experimental situation is in a rapid flux. We are certainly going through an exceptionally interesting period in particle physics. It is best to remain patient and unprejudiced while awaiting the outcome of future experiments before making a final judgement.

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Note Added

After completing the above account, we came upon additional (unpublished) data from SLAC on $\sigma(e^+ e^- \to \text{hadrons})$, which indicates the existence of another resonance at around 4.5 GeV with a width of a few tens of MeV—very much narrower than the broad resonance at 4.15 GeV (the P state in the paracharge scheme). In the paracharge scheme this new resonance may be interpreted as the states $S_-^{\circ\prime\prime}$ (*i.e.*, the ψ'') of a third 16-plet of vector mesons (a second 'radial excitation'). The corresponding $Z=0$ states *e.g.*, the ϱ'' and the P'', are then expected to be so broad as to be difficult to detect. However, since the $S_-^{\circ\prime\prime}$ carries paracharge $Z=\pm 1$, it is narrow enough for easy detection—in fact much narrower than the first P state at 4.15 Gev. Its decay, of course, can proceed by strong interactions to the lower Z-carrying states. This is an additional encouraging result for the paracharge scheme.

Fast breeder power reactors and their role in our nuclear power programme

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I am grateful for being given an opportunity to speak to you this evening. My talk will deal with Fast Breeder Power Reactors and their role in our Nuclear Power Programme. By nuclear power I mean essentially electricity generated from the energy liberated during nuclear fission. Although nuclear energy is widely known today, the first experimental demonstration of the production of electricity in this manner was carried out hardly two decades ago, curiously enough with a fast reactor. The reactor involved was EBR I (Experimental Breeder Reactor I) built in the United States in 1951. Even as this experiment was going on, plans had already been made for setting up large scale nuclear power reactors in many countries. In the two decades that have followed, nuclear power stations have become a reality not only in the so-called advanced countries but also here.

You are all undoubtedly aware that uranium is the key to nuclear power. The uranium available in nature is predominantly composed of two isotopes namely, U-235 and U-238. Of these, the former alone readily undergoes neutron-induced fission, but unfortunately its abundance is rather low, being only 0.7% or roughly 1 atom out of every 140. The first generation of power reactors all use uranium, some of them in the natural form and some with a slight enrichment of the U-235 percentage. Either way, the energy release occurs almost entirely due to the fission of U-235, and it is natural therefore to ask whether nuclear energy will get exhausted once all the U-235 available in nature has been fissioned. Fortunately, this is not the case and it turns out that even as nature's stock of U-235 is getting diminished, new fissionable nuclei not found in nature can be produced, and it is this aspect which makes nuclear energy particularly attractive. It is worth emphasising that there is no analog to this fuel stretching in the case of fossil fuels.

To understand nuclear fuel breeding, let us consult figure 1 which shows some of the isotopes of uranium and those of its neighbouring elements in the periodic table. In the case of uranium, we have already noted that only U-235 and U-238 are available in nature, the former in very much smaller quantity compared to the latter. Now let us suppose we have inside a nuclear reactor, some uranium either with the natural composition or in the enriched form. Even as fission chain reaction of U-235 nuclei is in progress, some of the neutrons produced during fission get captured by the U-238 nuclei, resulting thereby in the formation of the isotope U-239. This is unstable and disintegrates by successive radioactive decays to Pu-239 which, like U-235, is readily fissionable. Another fissionable nucleus not found in nature, but one which can be similarly prepared by neutron capture from available resources, is U-233. The starting material in this case is thorium, and again one must resort to neutron irradiation. Thorium consists almost entirely of the isotope Th-232 and by neutron capture becomes Th-233 which then transforms by successive decays to U-233 as illustrated in the figure. In this way, one can breed fresh nuclear fuel (i.e. Pu-239 or U-233) even as that endowed by nature, namely, U-235 is getting exhausted. It is in this fuel stretching that the promise of nuclear power really lies.

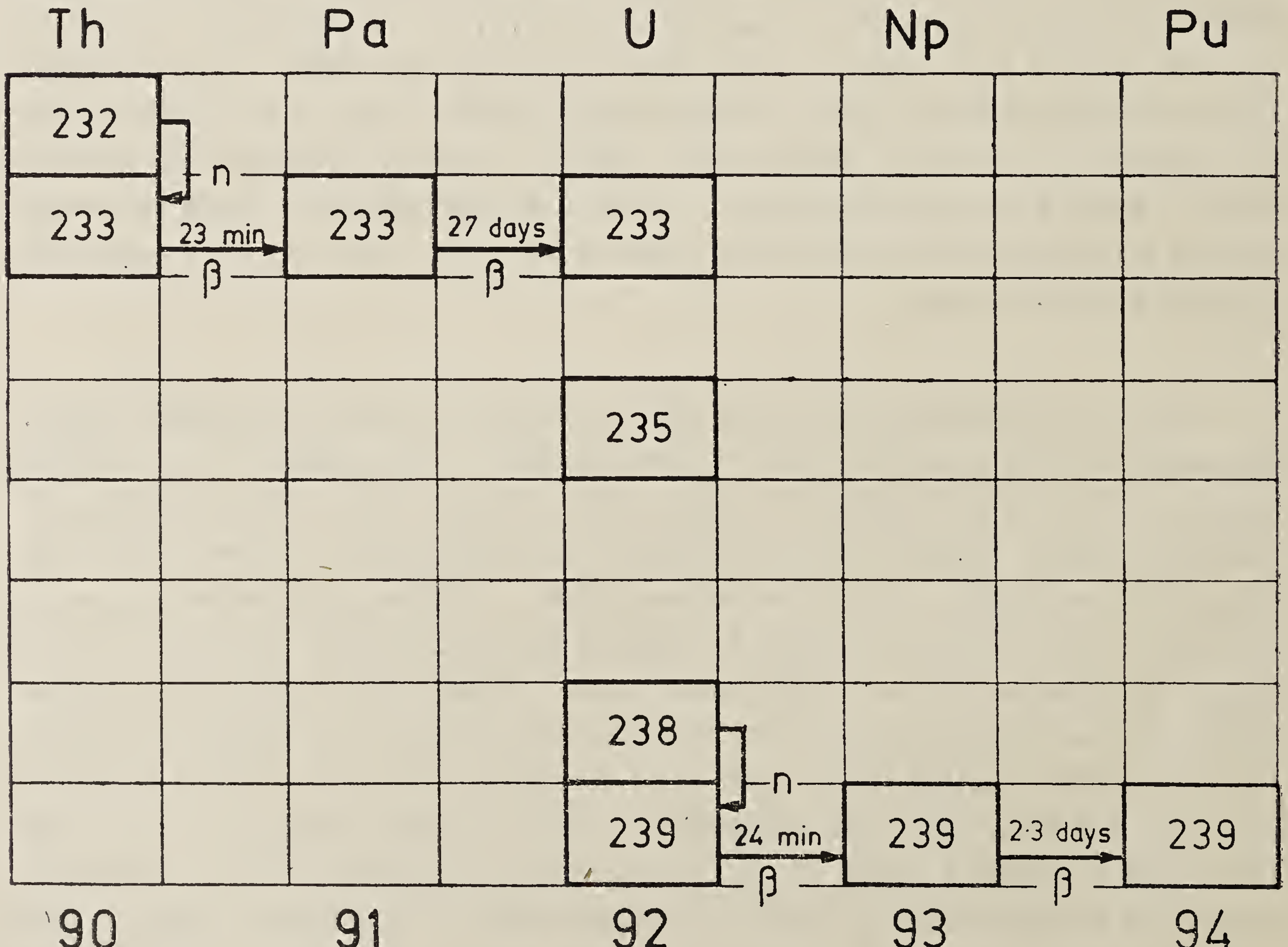

Figure 1. Portion of the periodic table showing the fertile and fissile nuclei. In the latter category are U-233, U-235 and Pu-239. Of these, U-233 and Pu-239 have to be manmade by the routes indicated.

So the crucial facts that have to be borne in mind when planning a nuclear power programme are :

(1) U-235 constitutes only a small part of the naturally available uranium,

(2) the more abundant isotope U-238 can be converted into Pu-239 which has favourable fissioning properties, and

(3) thorium which is available in plenty, can also be converted into a fissionable nucleus namely U-233.

With this background, I can now present a perspective of our own nucler power programme. As all of you are undoubtedly aware, this was given shape by a former distinguished Fellow of this Academy, the late Dr. Homi Bhabha. As early as 1958 Bhabha declared, "The total reserves of thorium in India amount to over 500,000 tons in the readily extractable form, while the total known reserves of uranium are less than a tenth of this. The aim of long-range atomic power programme in India must, therefore, be to base the nuclear power generation as soon as possible on thorium rather than uranium......The first generation of atomic power stations based on natural uranium can only be used to start off an atomic power programme...... The plutonium produced by the first generation of power stations can be used in a second generation of power stations designed to produce electric power and convert thorium into uranium 233, or depleted uranium into more plutonium with breeding gain...... The second generation of power stations may be regarded as an intermediate step for the breeder power stations of the third generation all of which would produce more uranium-233 than they burn in the course of producing power"

Figure 2 gives a comprehensive summary of Bhabha's strategy for nuclear power in India. The first stage involves the construction of thermal power reactors designed to achieve an optimum exploitation of our rather limited resources of natural uranium. The type of reactor chosen is the so-called CANDU-type concerning which I shall say more later. The basic merit of this reactor is its excellent neutron economy, as a consequence of which, it can, besides producing power, convert U-238 into Pu-239 with high efficiency. However, the plutonium produced does not come anywhere near replenishing the U-235 burnt up. Nevertheless, it is clear that if we have a chain of such CANDU-type power stations, then very soon we would accumulate a fair amount of plutonium. This plutonium may be used as fuel in a special type of reactor called the Fast Breeder Reactor. Like the CANDU

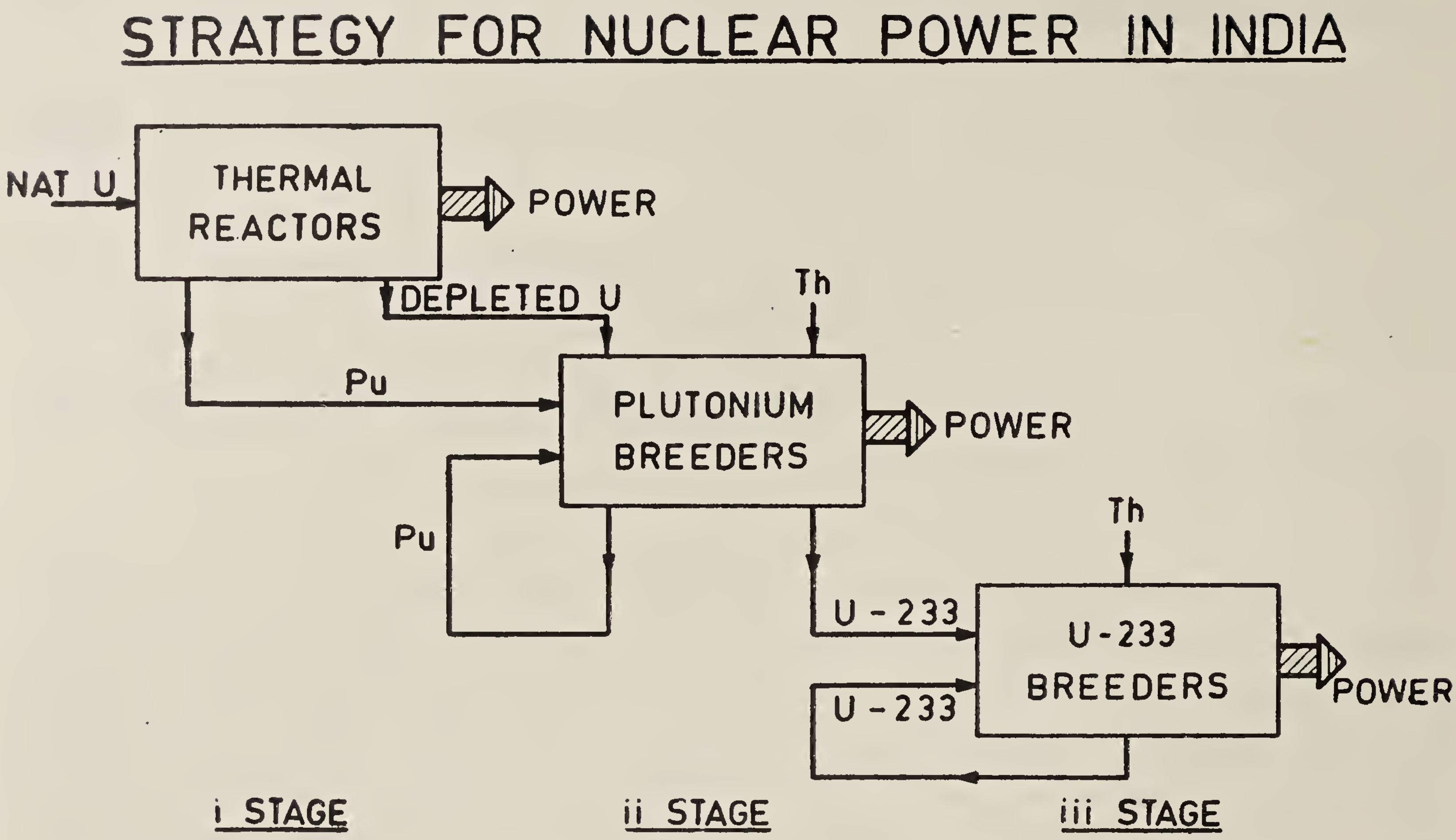

Figure 2. A schematic illustration of the three-stage programme envisaged by Bhabha for the development of nuclear power in India.

reactor,* the fast reactor also produces power, but its neutronic properties are such that it is extremely efficient in converting U-238 into Pu-239. Indeed, one can even produce more plutonium than is consumed and thereby achieve fuel breeding. One might wonder why fast reactors are not built to start with if they have such an attractive property. The answer is that apart from the fact that fast breeders need plutonium, the technology is extremely complicated. To return to Bhabha's nuclear power profile, in the second stage, it is planned to have plutonium breeders which will start by using the plutonium produced in the first stage and then convert the depleted uranium left behind in the first stage into more plutonium. The excess plutonium produced by such breeder power stations can be utilized to build fresh fast breeders. Some of these can also be utilized for producing U-233 by irradiating thorium. Eventually our plutonium will get exhausted, but by this time we should have accumulated enough U-233 to go into a Thorium–U–233 cycle. On account of our very large reserves of thorium, this cycle can easily meet our energy needs for at least a thousand years if not more.

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*The CANDU reactor is an example of what is called a thermal nuclear reactor *i.e.* one in which the energy of the neutrons causing fission is of the same order as the usual thermal energies of molecules at 300 K *i.e.* $\sim$ 0.025 eV. In a fast reactor on the other hand the average energy of neutrons causing fission is very much higher being $\sim$ 100 keV.

The first of the three stages conceived by Bhabha is well under way. One CANDU type reactor with a capacity of 218 MW (e) is already in operation at Kota in Rajasthan. This reactor uses natural uranium as fuel, and heavy water both as moderator and as coolant. A second unit is also being set up in Rajasthan; it is very nearly complete and will become operational soon. Two such units, each capable of electrical output of 235 MW(e), are rapidly nearing completion at Kalpakkam near Madras. Preliminary work has just started on two more units of a similar nature at Narora in Uttar Pradesh.

The technology for building these reactors, especially on the nuclear side, has been indigenised completely. The uranium is mined locally, and the fuel is fabricated in Hyderabad based on the techniques and processes evolved at the Bhabha Atomic Research Centre, Trombay. Steps have also been taken to manufacture heavy water in the country, and plants are being set up at Baroda, Kota, Talcher and Tuticorin. Of these, the Baroda plant in particular, is very close to becoming operational while the others are in various stages of construction. The electronics and the control instrumentation is made entirely at the Electronics Corporation of India Ltd., and the engineering hardware is also progressively being made almost entirely in the country. I am sure you must have heard about all this at various times and I shall therefore not go into the details. It suffices to know that the first stage is well under way and that a good part of the technology required is available indigenously.

Before discussing our plans for the second stage, a few words about fast breeders are necessary. Basically a breeder may be defined as a reactor that produces more fissionable atoms than it consumes. Generally speaking, in all reactors, some fissionable atoms are always produced even as others undergo fission. For example, in the CANDU-type reactor, while U-235 is undergoing fission, some U-238 is getting transformed into Pu-239. However, the number of plutonium atoms produced is very much smaller than the number of U-235 fissioned. In this context, one may define a quantity C known as the conversion ratio given by (El-Wakil 1971)

$$C = \eta - 1 - L.$$

where η is the average number of neutrons produced per neutron captured (the capture may or may not produce fission and we are including both possibilities) ; L is the number of neutrons lost by leakage etc., per neutron absorbed in a fissionable nucleus. In the CANDU reactor, $C < 1$, but in a fast breeder, C can be greater than one ; in this case more fuel is produced than is consumed and one has fuel breeding. The maximum possible value of C is obtained when $L = 0$, from which it is obvious that for breeding to be even possible, η must be greater than 2. Figure 3 shows η as a function of neutron energy for the three fissionable nuclei (El-Wakil 1971). It should be clear from this why fast-neutron fission is preferable for breeding plutonium. On the other hand, notice that for U-233, one could possibly achieve breeding even with thermal-neutron fission. In other words whereas for plutonium breeding one *must* have a reactor in which neutrons have fairly high energy i.e. a fast reactor, U–233 breeding could be achieved with a thermal reactor system. In fact, the thorium breeders of the future are expected to be thermal reactors.

The breeder principle is a very attractive one, but nature does not give this concession without a price; and the price we have to pay is technological

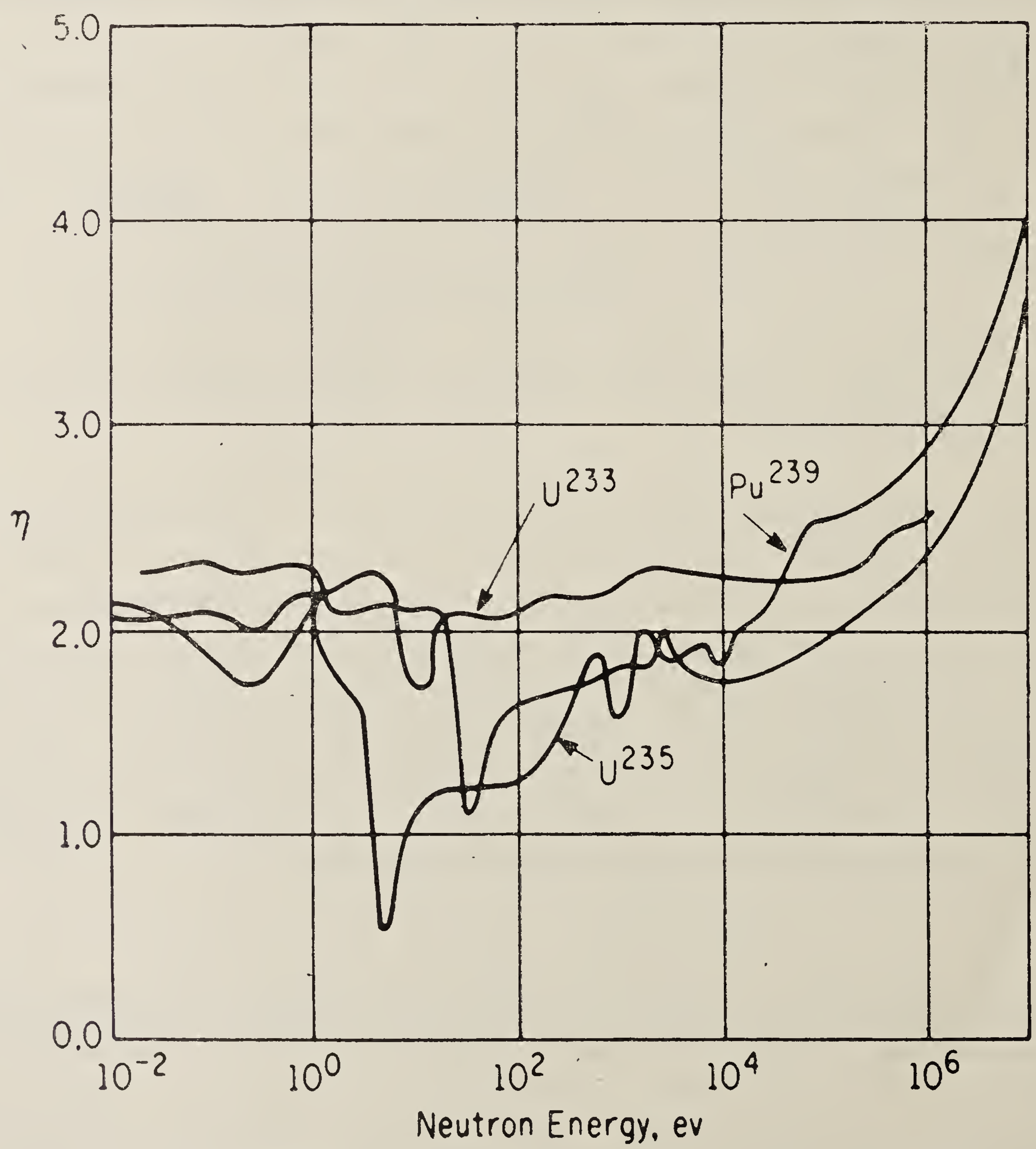


Figure 3. η as a function of neutron energy for the three fissionable nuclei (after El-Wakil, 1971).

complication. Reactor physics considerations dictate that the concentration of fissile atoms in fast reactors must be rather high compared to that in thermal reactors, and as a result, the power densities are very much larger. Tables 1 and 2 attempt to convey the severity of environment in a fast reactor relative to that in a comparable thermal reactor. In a fast reactor, one has not only to deal with higher temperatures but also very much higher neutron fluxes and higher neutron energies. The very high power densities call for a coolant with good heat transfer properties and the coolant presently favoured universally is liquid sodium.

Table 1. Relative performance criteria for fuels for fast breeder reactors and therma reactors of comparable electrical output.

Parameter		Required improvement factor for fast reactor fuel vis-a-vis the thermal reactor
Burn up (MWday/ton)		5–10
Fuel power density (MW/ton)		3
Core power density (kW/litre)		10
Neutron flux (neutrons/cm^2 sec)		30
Neutron exposure of materials of construction	(neutron/cm^2)	50
Thermal shock (°C/sec)		5–10

Table 2. Comparison of some thermal and fast reactors. The CIRUS and FBTR are relatively small. research reactors. The former is at Trombay and the latter is being built at Kalpakkam. Phenix is a fast breeder power station in operation in France while MAPP is a thermal power reactor under construction at Kalpakkam

Reactor	Power	Core size Ht×Dia (meters)	Max. Flux (n/cm^2 sec)
FBTR	42.5 MW (th)	0.32×0.46	3×10^{15}
CIRUS	40.0 MW (th)	3.05×3.05	6.5×10^{13}
PHENIX	250 MW (e)	0.85×1.35	7.2×10^{15}
MAPP	235 MW (e)	5.00×4.50	1.3×10^{14}

From the point of view of sodium flow, the present day fast reactors can be broadly classified as belonging to the pool—or the loop type. These are illustrated schematically in figures 4 and 5 which are self-explanatory. In both types of reactors, there is an intermediate sodium-to-sodium heat exchanger (IHX) in which the heat removed from the core by liquid sodium is transferred to the second loop, also carrying sodium. The latter then transfers the heat to steam in a specially designed steam generator. During its passage through the reactor core, the sodium in the primary circuit

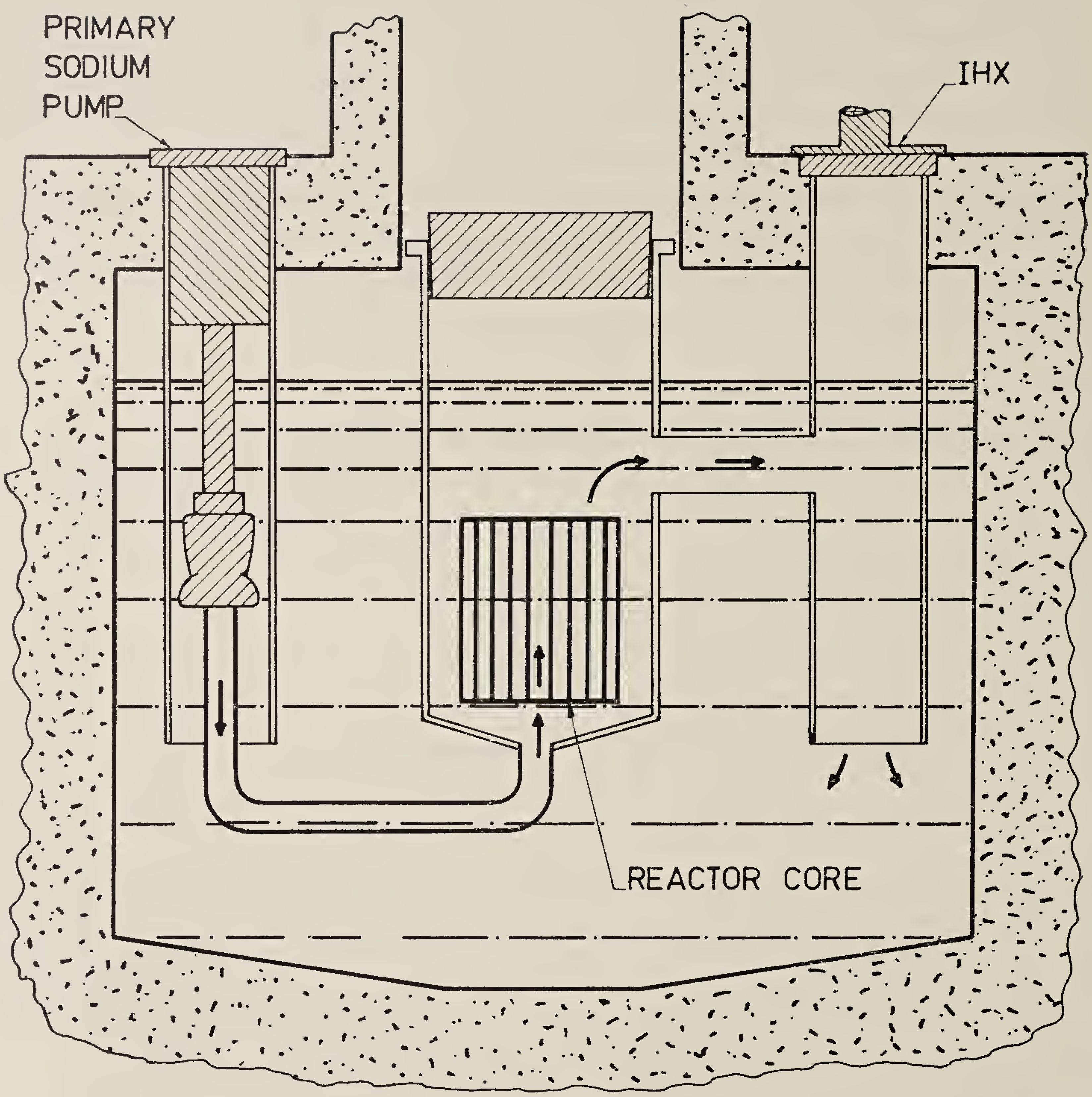


Figure 4. Schematic drawing of the pool-type fast reactor. Here the core and the primary heat-transfer system are all located in one large sodium-filled tank.

inevitably becomes radioactive. The IHX acts as a buffer and prevents the possible escape of this radioactivity into the steam circuit. Of the two coolant configurations mentioned above, the first requires a large quantity of sodium. The primary containment vessel is also huge, contributing to the cost. Offsetting this is the advantage that the pool always provides coolant to the core whereas in the loop system one can conceive of a loss-of-coolant accident triggered by sodium leakage in the primary system. Coolants other than liquid sodium like mercury and sodium-potassium alloys have been tried earlier. The advantage of sodium is that it is a solid at room temperature. In the event of a leak in the plumbing, the sodium diffusing out of the leak tends to solidify, providing thereby a natural sealing action.

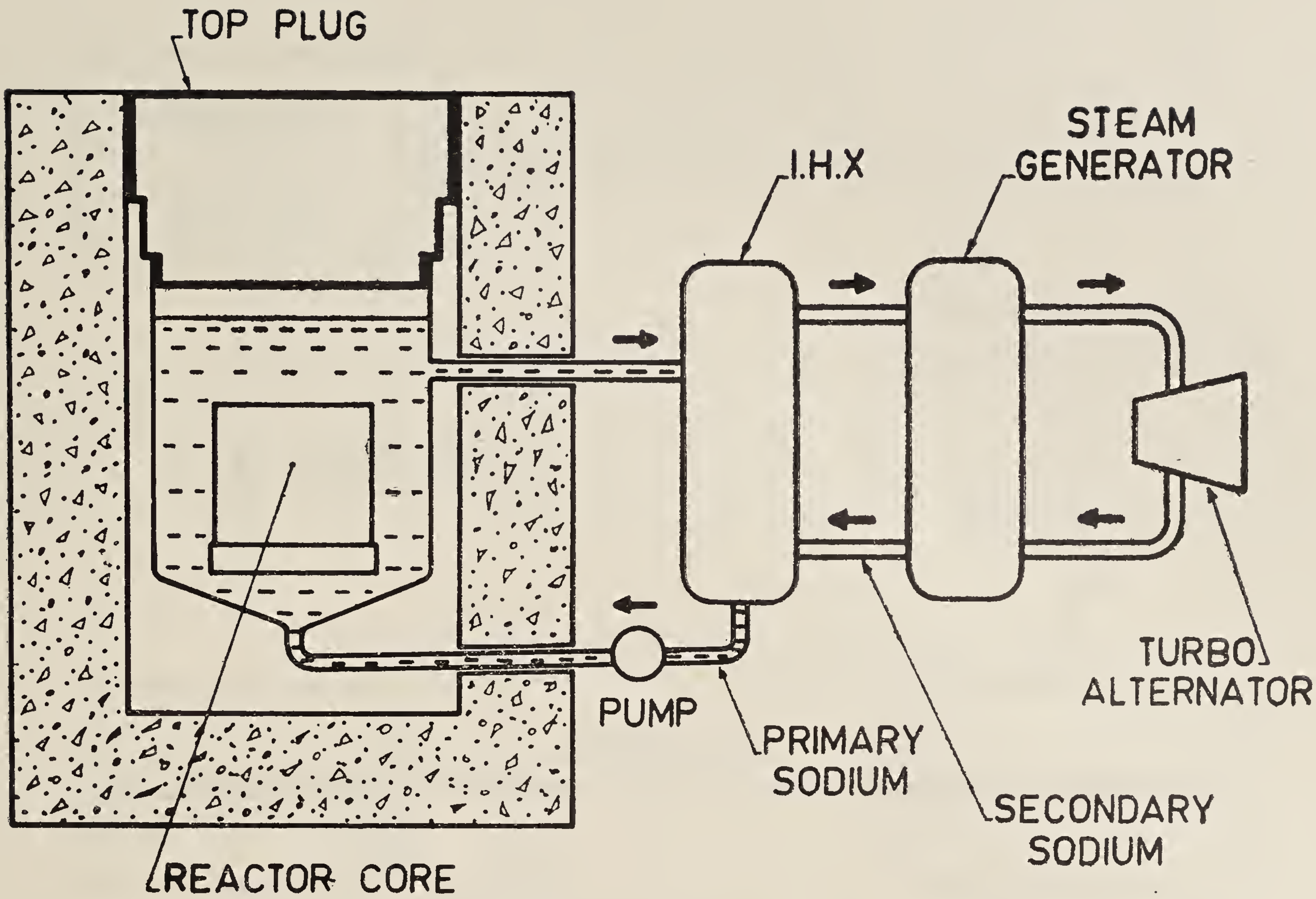


Figure 5. Schematic drawing of a loop-type fast reactor. Here the reactor core is contained in a small vessel and the primary sodium is pumped through the vessel and then piped to the IHX which is outside the reactor.

The fast breeder principle has by now been established by experiments, and it is a proven fact that one can build reactors which produce more fuel than they consume. However, from the economics point of view, what is of importance to a breeder reactor is its doubling time. This is the time required for the reactor to produce as many new fissionable nuclei as the total number of fissionble nuclei that are normally contained in the core and tied up with the reactor fuel cycle. The latter includes fuel fabrication, fuel reprocessing etc., and is an important aspect of the fast reactor programme. The point may be better appreciated by referring to figure 6 which shows schematically the fuel cycle. Supposing we start with fresh fuel in a fast breeder reactor. The fuels currently used are mixed oxides of plutonium and uranium. After a while some of the plutonium would have fissioned but fresh plutonium atoms would also have been produced by neutron capture in U–238, and one would like to recover this freshly produced plutonium. For this purpose, the irradiated fuel has to be removed from the reactor and sent to the fuel-reprocessing plant. However, to keep the reactor running some fresh fuel must be added. Now the irradiated fuel will be very highly radioactive and cannot be immediately

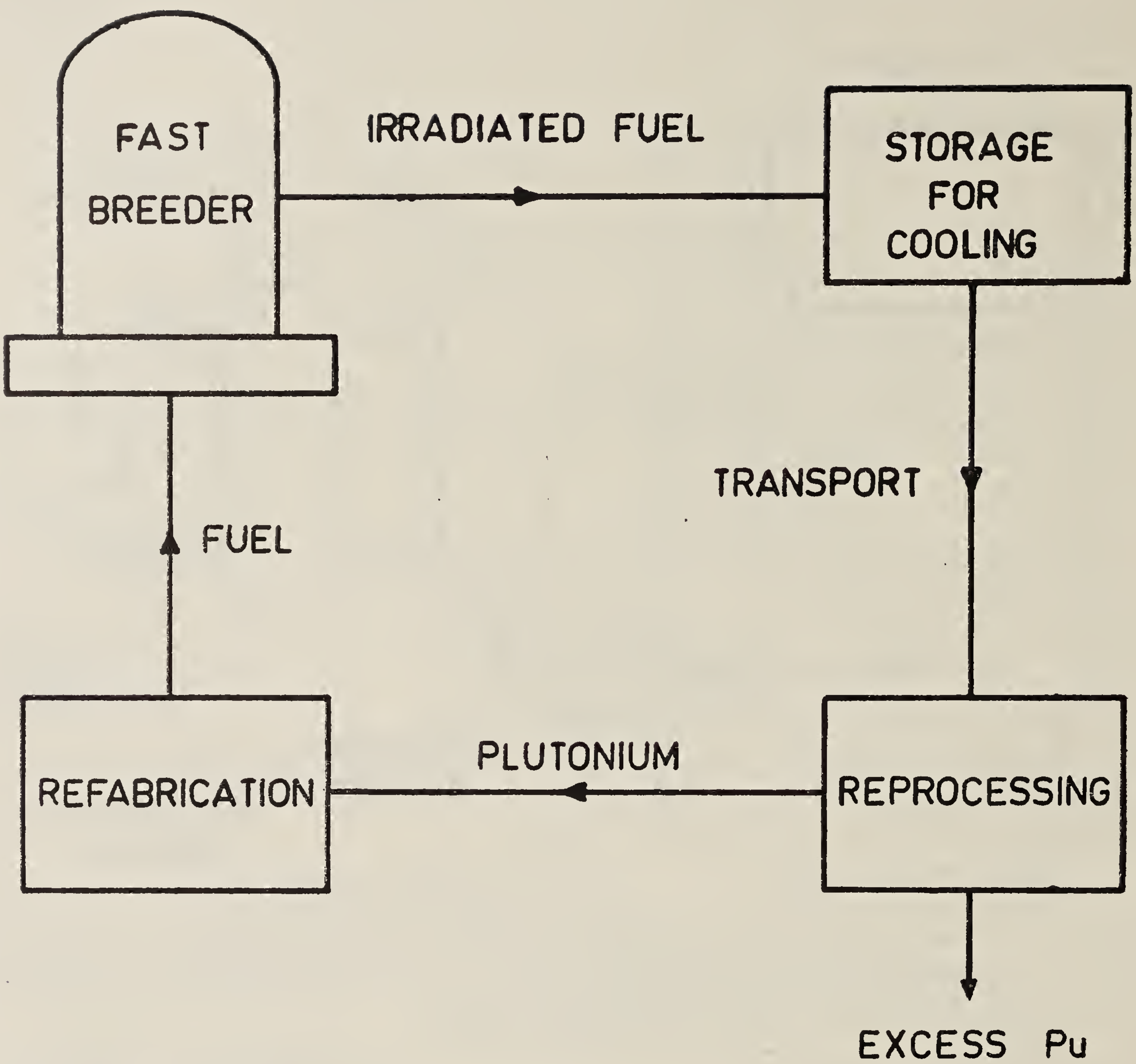
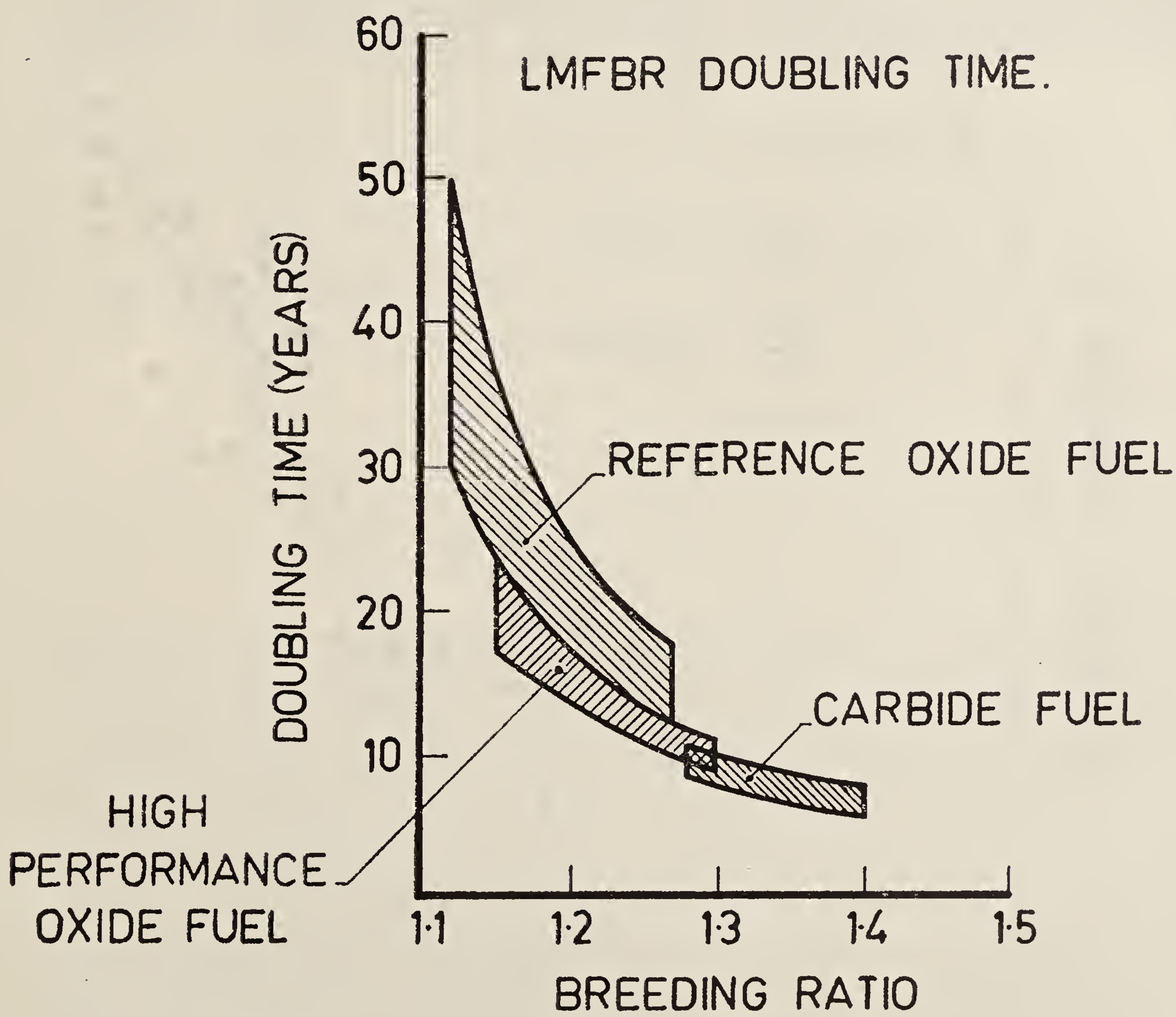


Figure 6. Schematic drawing of the fast reactor fuel cycle.

reprocessed. A certain waiting time is mandatory during which the radioactivity is allowed to decay to manageable levels. In this period, the fuel is stored in such a way that the heat liberated during radioactivity decay is properly dissipated. The fuel then is sent to the reprocessing plant where some more time will elapse before the uranium and plutonium are separated. The plutonium separated must then be sent to the fuel fabrication plant for fabricating fresh fuel. Every reactor will thus tie up a certain amount of plutonium associated with the plutonium cycle covering both fuel fabrication and reprocessing. This inventory will be larger than the plutonium actually present in the reactor at any given time, and the excess plutonium production must be with respect to the inventory in the whole cycle. From the point of view of expanding nuclear power production therefore, what one looks for is a system with a small doubling time vis-a-vis the whole cycle. The present day mixed-oxide fuels (i. e. $U0_2 + Pu0_2$ homogeneous mixtures in pellet form) no doubt lead to doubling but the doubling times are inordinately long. Figure 7 gives an idea of the expected doubling times for various types of fuels (Cunningham 1974). As can be seen, one must graduate soon to carbide fuels to achieve respectable doubling times. These fuels are tricky and apart from the difficulty of making them cheaply, there are also problems in finding materials compatible with them which can serve as clad. Fuel development then, is an important aspect of fast reactor technology.

Another aspect equally important is the development of materials of construction. As already pointed out, reactor materials have to face very high fast neutron fluxes and that too at fairly high temperatures. The fast neutrons produce extensive atomic disorder leading thereby to changes in



LMFBR DOUBLING TIME AS A FUNCTION OF BREEDING RATIO

Figure 7. Doubling times for fast breeders for some of the fuels in use or contemplated.

the mechanical, thermal and various other properties. Figure 8 gives some idea of the type of damage fast neutron can cause (Hudson *et al.* 1971). What you see here is an electron microscope picture of tiny holes or voids produced by fast neutron bombardment. As a result of void production, atoms get displaced and the material as a whole swells. Swelling can be as large as 10%, and obviously can play havoc if the components have been made to close tolerances. Figure 9 gives an idea of swelling as a function of neutron dose for a particular type of stainless steel (Norris 1972). Data such as shown in this figure have been obtained by irradiating for several years in present day experimental fast test reactors. These test reactors are very much smaller than the power reactors one hopes to build in the future and therefore one has the problem of extrapolating to tomorrow's reactors with today's systems. To put it differently, one has to anticipate the damage expected at a fluence or

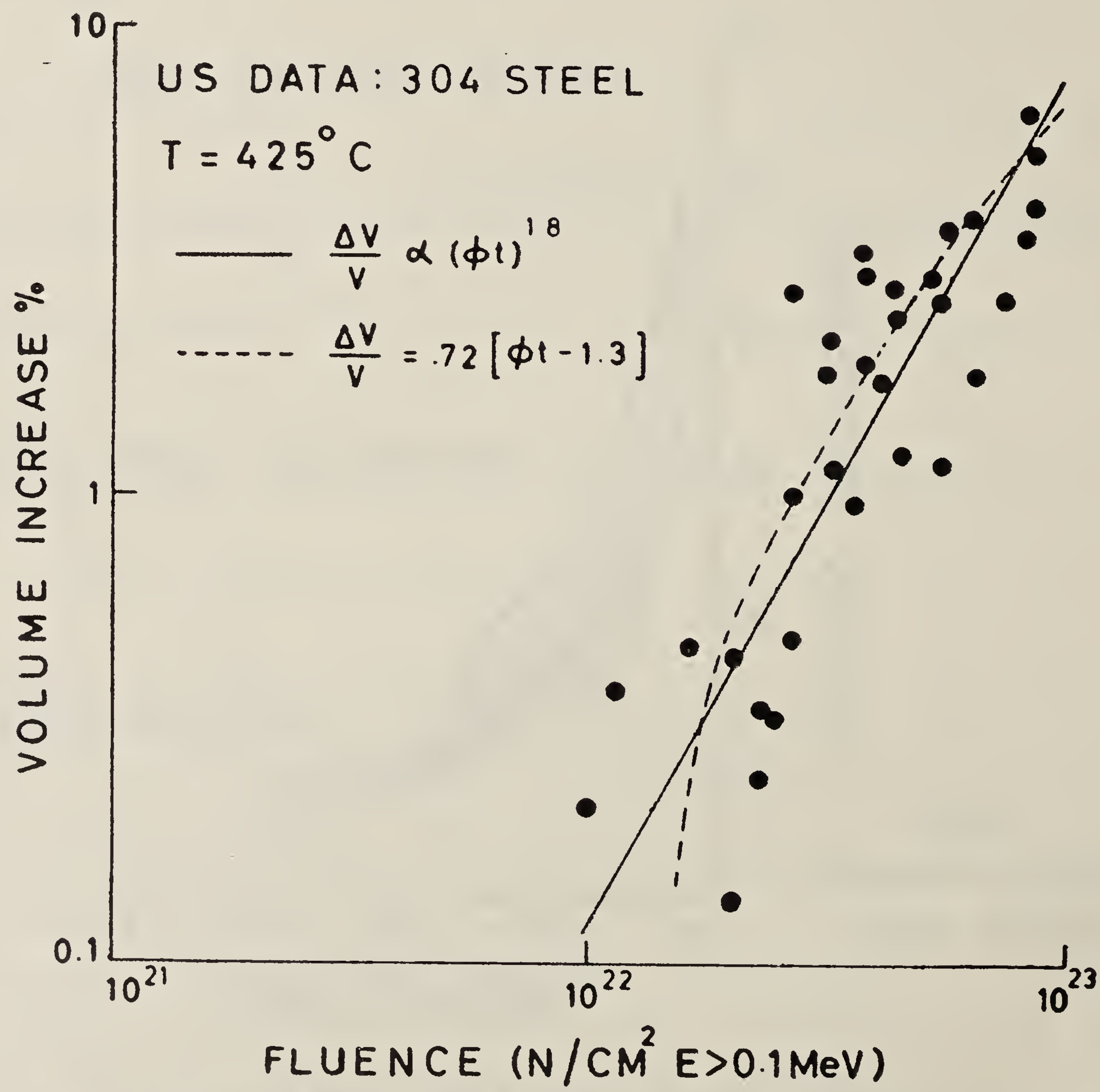


Figure 9. Data for the swelling of 304 stainless steel as a function of neutron dose. Irradiation in present day test reactor can lead to fluences $\sim 3\text{-}5 \times 10^{22}$n/cm^2 in about two years. The correponding figure for future power reactors could be at least three to five times greater. Irradiation data at $\sim 10^{23}$ fluence is very hard to obtain at present. They must therefore be guessed by extrapolation or obtained by simulation.

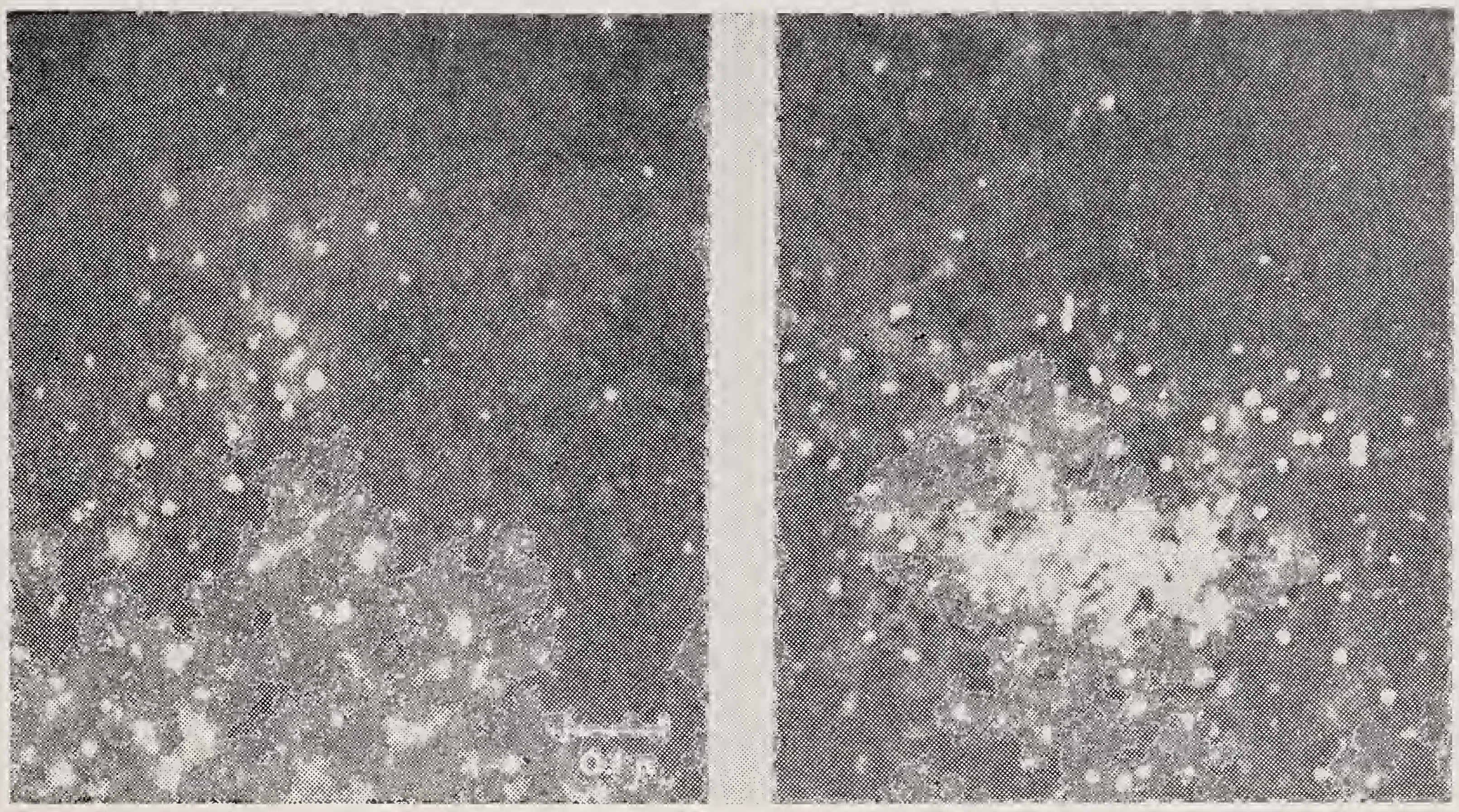


Figure 8. Electron microscope pictures of voids in nickel produced by (a) neutron irradiation in the Dounreay Fast Reactor (DFR) and (b) in a Variable Energy Cyclotron with carbon ions. The latter figure serves to highlight the utility of the cyclotron in simulating neutron damage. Note the cyclotron can produce as much damage in one day's irradiation as two years irradiation in a fast reactor like the DFR (after Hudson *et al.*, 1971).

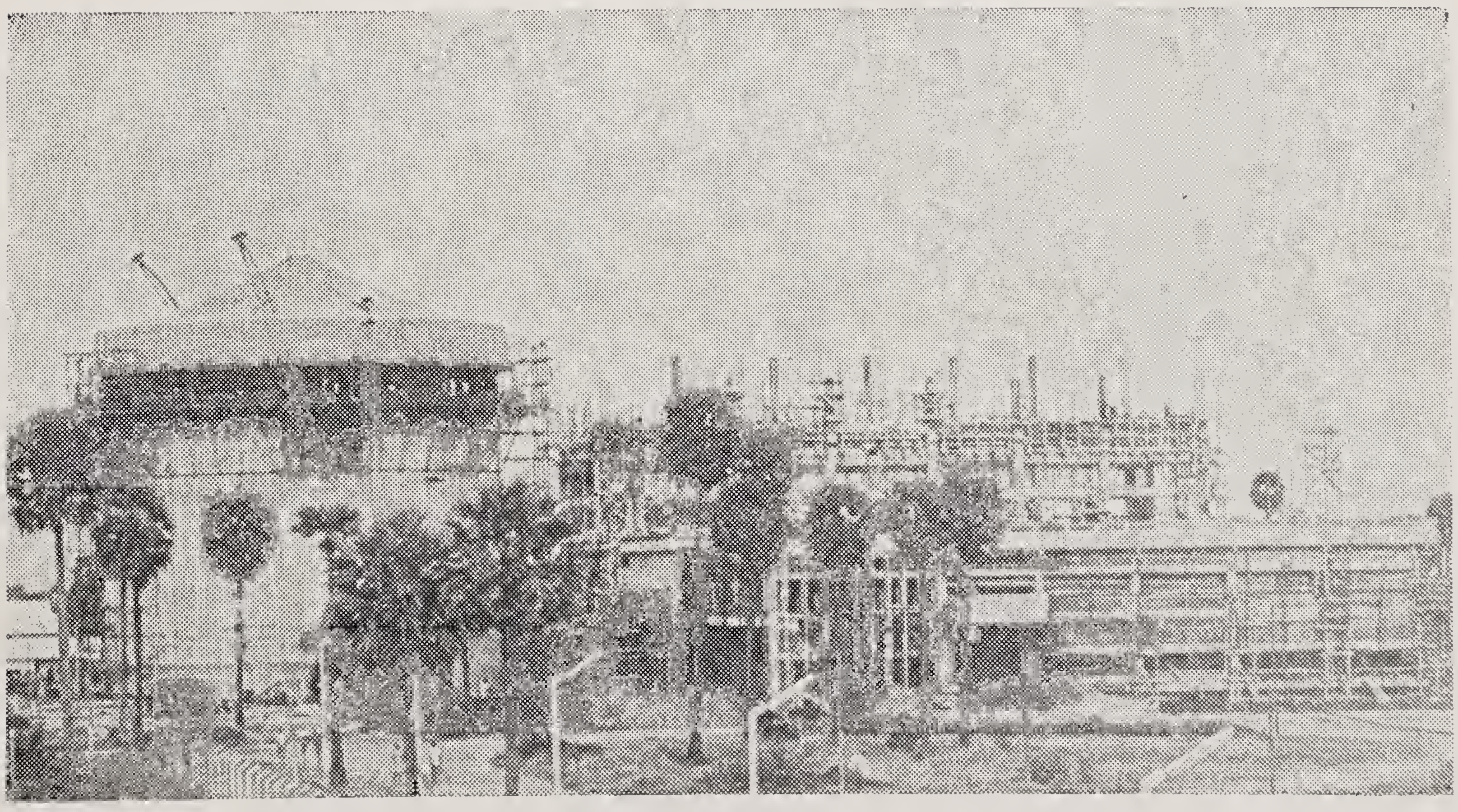


Figure 10. Photograph showing the FBTR under construction at Kalpakkam.

irradiation dose level much higher than that which can be easily reached in today's systems. Inaccurate extrapolations may lead to overdesign and concomitant economic penalty. It is understandable therefore that a considerable amount of R & D work is going on throughout the world to understand the phenomena of radiation damage. My own research work at present is to some extent in this area.

Returning to the discussion of our Nuclear Power Programme, even during Bhabha's life time, plans had been made to set up a medium-size experimental fast reactor for coming to grip with breeder technology. Subsequently, the fast breeder programme was examined in greater detail and a blue-print for the development of fast breeder technology was evolved at Trombay. To implement this programme, the Department of Atomic Energy created in 1971, a new Centre called the Reactor Research Centre (RRC) to which I belong. This Centre is located at Kalpakkam adjacent to the site of Madras Atomic Power Project. The main reason for locating the breeder development programme outside of Trombay was that a metropolitan city was not considered an ideal location for an experimental fast power reactor.

As elsewhere, our Research Centre also will be preoccupied with the development of structural materials and of fuel. The most important research facility at the Centre will be the Fast Breeder Test Reactor (FBTR). This test reactor will employ mixed-oxide fuel, and will have a thermal output of around 40 MW. Although the reactor is basically intended to be used as a powerful neutron source for our irradiation experiments, it is also intended to obtain incidentally some power-plant experience by generating electricity. In fact we expect to produce around 12 MW (e). Building the reactor itself will give us considerable experience in fabrication technology as the specifications are generally an order of magnitude more stringent than in the case of thermal reactors. It is gratifying that almost all the parts of the reactor are being built in the country. But unfortunately the materials of construction could not all be procured indigenously. Our Centre will therefore endeavour to develop the knowhow for the production of such superior grade materials likely to be required in the future. Figure 10 shows a view of the FBTR under construction.

Other than the FBTR, RRC will have laboratories devoted to radiochemical, radiometallurgical and fuel reprocessing investigations, as also for basic studies in materials. Once the FBTR is built, we plan to undertake intensive experiments and come up with a blue-print for a 250-500 MW (e) fast breeder station say, by the early eighties.

The status of fast reactor technology elsewhere in the world may be discerned by referring to tables 3 and 4. It will be seen that several countries have graduated to fairly large scale power stations and in fact the PHENIX station in France has had an excellent record of operation, amply fulfilling the hopes pinned on large fast reactors. Our own equivalent of PHENIX would probably come by the late eighties.

Table 3. List of some of the medium-sized fast reactors already in operation.

Reactor	Country	MW (th)	MW (e)	Year
DFR	United Kingdom	60	15	1959
EBR II	United States	62	20	1963
Fermi	United States	200	67	1963
Rapsodie	France	40	—	1967
BR-60	USSR	60	12	1970
BN-350	USSR	1000	150	1972
Phenix	France	600	250	1974
KNK-2	West Germany	58	20	1974

Table 4. List of some of the fast reactors under construction.

Reactor	Country	MW (t)	MW (e)	Year
FBTR	India	42-5	12.5	1978
PFR	United Kingdom	600	250	1976
JEFR	Japan	100	—	1976
SNR	West Germany	730	300	1976
FFTF	United States	400	—	1976
Super Phenix	France	—	1200	1981
CFR	United Kingdom	—	1320	1983

Let me digress here for a moment and make a brief mention of a novel proposal made recently for producing electricity from nuclear energy. The concept is illustrated in figure 11 and the programme carries the code name 'Pacer' (Science 1975). The basic idea is to use a nuclear explosion instead of a reactor for producing steam. The authors of this idea suggest that thermonuclear devices be periodically detonated in deep underground salt domes. The domes are initially filled with water and when the device is detonated, the water gets converted into high-temperature, high-pressure steam. The steam is then taken up to run a turbine and the condensed water is allowed to flow back. Although power can be produced, the proponents of the Pacer system are actually envisaging it as U–233 Breeder. In this way they hope to short-circuit the fast-breeder and the thorium-breeder stages and make U-233 available through "explosion breeding". Two advantages are claimed for this. Firstly by avoiding the building of fast breeders, one can circumvent the traffic of large amounts of plutonium and hence the possibility of hijacking by unscrupulous gangsters who could

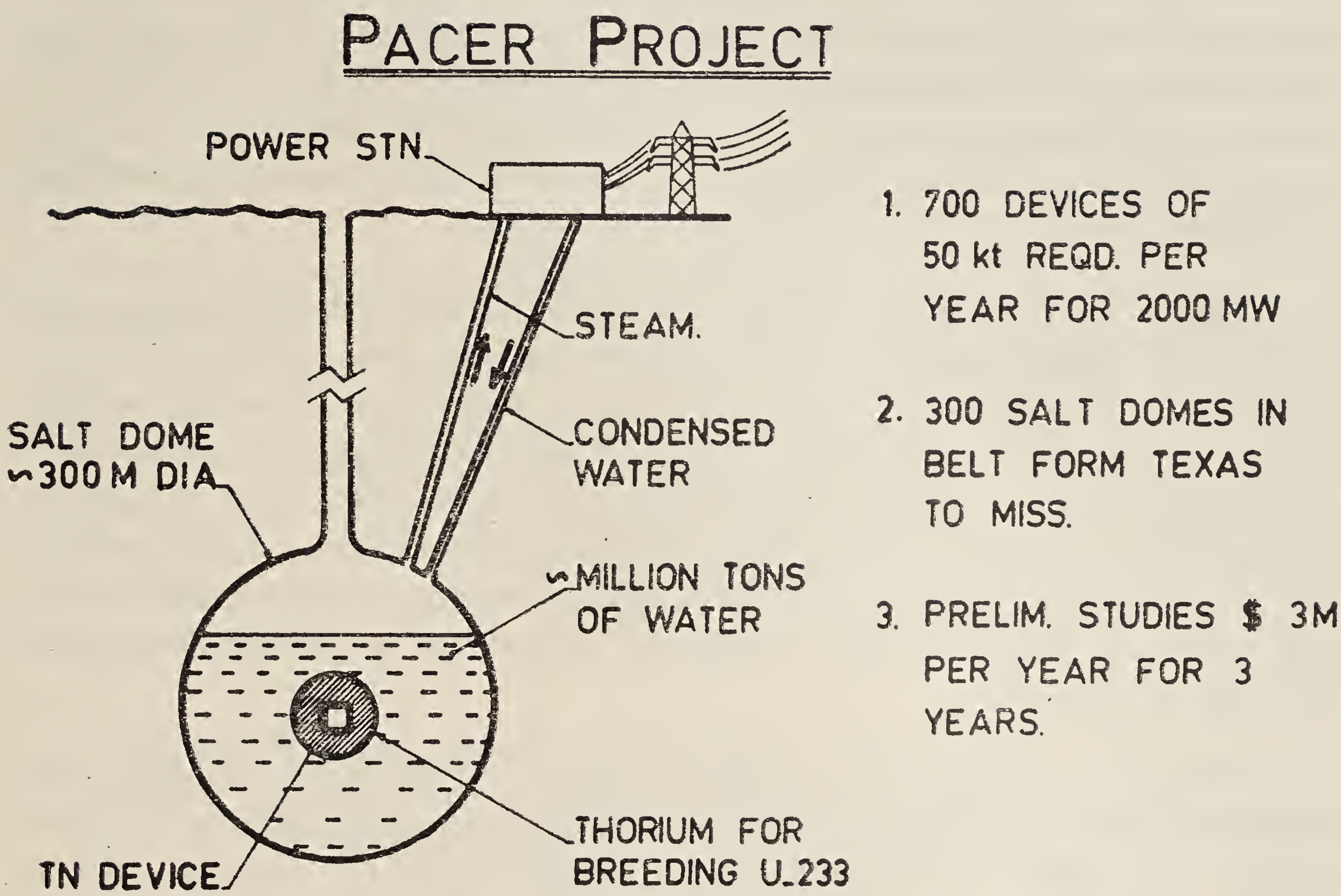


Figure 11. Schematic illustration of the Pacer project.

use the plutonium to make weapons. Secondly no new reactor technology is required since the U–233 bred could be diluted with natural uranium to make up the type of uranium required for the present day type of thermal reactors. The fuel for such reactors can be transported quite safely since it is not of weapon's grade and therefore not susceptible to hijacking. While the authors of the Pacer Concept are promoting it very enthusiastically, there is sharp criticism of it also.

Another possible source of nuclear energy is that released in nuclear fusion. The later refers to the synthesis of a bigger nucleus from smaller nuclei. You must certainly be aware that fusion is the source of energy production in the Sun. The reaction envisaged for power production here on earth is the following one involving deutrium and tritium :

$$D + T \rightarrow He^4 + n + 17 \text{ MeV}$$

In his Presidential Address to the First International Conference on the Peaceful Uses of Atomic Energy held in Geneva in 1955, Bhabha declared, "It is well known that atomic energy can be obtained by a fusion process as in the hydrogen bomb and there is no basic scientific knowledge in our possession today to show that it is impossible for us to obtain this energy from the fusion process in a controlled manner. The technical problems are formidable but one should remember that it is not yet fifteen years since atomic energy was released in a pile for the first time by Fermi. I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades. When that happens the energy problems of the world will truly have been solved for ever."

Nearly two decades have passed since Bhabha's forecast but fusion power has not yet become a reality. This, however, has not been for want of trying. A considerable amount of effort has been put in all over the world, and the delay has been due to the appearance of unexpected problems associated with plasma instabilities. These problems have taken a long time to be understood and solved, and after several years of inching forward, the climate today is one of optimism. Even so, controlled fusion has not yet been achieved, and it is doubtful whether fusion technology as such will get established before the turn of the century.

Before concluding, I must make a reference to the fears that have been expressed concerning nuclear power. By and large, these fears are of recent origin even though nuclear power has been with us for two decades. About 10 years ago, nuclear power was accepted by everybody as the only available and established source of abundant energy. However, the widespread environmental awakening in the late sixties has put nuclear industry on the defensive. Basically, two doubts have been expressed concerning nuclear power. The first is the disposal of radioactive waste, and the second is the possibility of an accident. For purposes of record it must be mentioned that long before the public started debating these questions, nuclear industry has given thought to these problems. In fact, not only did nuclear industry exert very hard to tackle the problems of waste disposal, but it had also created surveillance groups which police the environment and keep close watch. Furthermore, every power plant is designed in such a way as to minimise the damage from the worst conceivable accident. I do not know of any other industry wherein such a serious study of maximum credible accidents is made.

Public concern regarding risks associated with nuclear industry is understandable especially when we recall that Mankind's Baptism to nuclear energy was through Hiroshima and Nagasaki. However, it is important that the issues be analysed and evaluated at a technical level rather than engaging in a polemical debate. Here is an example of what I think is unsupported exaggeration. The Conservation Society in a pamphlet says, "If something goes wrong, the core of the reactor may get hotter and hotter until the containing vessel is destroyed and the radioactive contents are sprayed out over the surrounding land, probably killing tens of thousands of people, injuring far more, and leaving hundreds of square miles of land uninhabitable for generations." Such a horrifying picture has no quantitative basis. Safety groups trained in the scientific analysis of accidents, carry out for every reactor concept, a thought experiment in which the reactor is assumed to undergo the worst *scientifically conceivable* accident The consequences of the accident are then fully analysed, and in particular the reactor building is required to be designed to withstand the consequences of the maximum credible accident (MCA) and contain the radioactivity to the maximum possible extent. While there may be disputes as to the actual numbers arrived at in such MCA analysis, no critic has ever challenged on technical grounds the *magnitude* of the credible accidents, and they come nowhere near to the sort of accidents required for fulfilling the Conservation Society's picture.

The opponents of nuclear power often talk of risks. Risk is inherent in modern technology and there is no such thing as zero risk. In fact, society tacitly accepts the concept of risk. For instance, a risk of death to an individual of $\sim$ 1 in 1000, is considered totally unacceptable. But as the risk level decreases, public concern also diminishes. At 1 in 10,000 there is no doubt still enough concern to warrant the expenditure of public money to minimize the risk, but below 1 in 100,000 the risks are of less concern (Lister 1975). They are generally treated as individual risks and combated by warnings! Discussion of risk must be on a comparative basis and before raising a hue and cry, one must objectively assess the relative risks in nuclear industry and say, in the transporation industry. The same arguments apply to the risks of genetic damage also. The point I am trying to make is that hysteria should be avoided and that the issues must be examined in a rational manner. As I remarked earlier, public debate and concern is understandable, but the public must be carefully educated and made aware of the scientific and technological pros and cons. That should be, I think, the responsibility of the learned scientific bodies like this Academy.

To sum up, we have today a great need for augmenting our energy resources. This everyone is aware of. The fossil resources are definitely likely to be exhausted sooner or later; this is particularly true of oil. Coal may last a little longer, but there are many problems there also. Among the new resources, the three major prospective candidates are fission energy, fusion energy and solar energy. Concering the latter I have not said anything in this talk since it is so much in the news these days. The relative pros and cons of the candidates are briefly summarised in table 5. Each option has a price-tag and it is for society to debate the price and make the choice. There is of

Table 5. Brief comparison of the three principal sources of energy of the future.

	Fission	Fusion	Solar
1. Resources	Can lest at lcast 1000 years	Unlimited	Unlimited
2. State of technology	Proven	Not yet established	Commerical exploitation not yet demonstrated
3. Pollution	Radioactive waste disposal a problem, but manageable	same as fission but perhaps to a lesser extent	Clean ?

course one more choice and that is to go back to a life of simple living and high thinking as Gandhiji often recommended. Besides sparing us rat races and ulcers, such a life is not energy expensive. I do not know whether mankind is mature enough to realise the wisdom of this suggestion. If it is not and would prefer a life style providing creature comforts, then additional sources of energy must be found. The die must be cast soon, and in terms of technological readiness at least, fission energy seems the most promising option.

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