Directions of Particle Physics*1

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§ 1. Modes of quest in particle physics

Particle physics as a subdiscipline in physics owes its origin to E. Lawrence for its experimental aspect, and to H. Yukawa for its theoretical aspect. The significance of their contributions lies not only in the particular work they did, but more importantly, in the fact that each established a basic methodology for the particle physicists to follow. These methodologies have turned out to be so powerful and fruitful that we are still following them. On the experimental side, this is most evident in the current activities going on at various accelerator laboratories all over the world. Their particle energies are now reaching a million times that of Lawrence's first cyclotron.

The purpose of my talk, however, is to concentrate on the theoretical side. In an attempt to understand the properties of nuclei with their two mysterious types of interactions, the strong and the weak, he unwittingly, so to speak, hit the tip of an iceberg which was to become the whole discipline of particle physics. I doubt that Yukawa himself, when he hypothesized his meson in 1935, would have anticipated the proliferation of elementary particles we have discovered since then.

It seems to me that Yukawa's approach had a heuristic and phenomenological tone. Because of this nature, it served as a useful guiding principle to explore uncharted and ever surprising new worlds, just as Lawrence's cyclotron and its descendants served as useful experimental tools to go with it. Yukawa's approach had both conservative and radical sides. He was conservative in the sense that he pursued the logical consequences of relativistic quantum field theory (which was in its infancy at that time) rather than vaguely anticipating a more radical solution of the problem of nuclear forces, a belief often held by his contemporaries. But he was radical in the sense that he did not hesitate to speculate on the existence of new elementary particles which had not been seen. According to him, his meson had not been seen in everyday life, not only because it had a large mass, but also because it was unstable. Strong binding and weak instability are the two peculiar features of nuclei, but one might feel uneasy to accept the notion of an unstable but elementary particle unless one has a pragmatic mind, as did Yukawa and, before him, Fermi. It is a notion we have come to accept without understanding its deep reasons even now. At any rate, Yukawa solved the problem of nuclear forces by dividing it in two inherently different parts: the theoretical framework in which to describe nature, and the substantive question of what entities exist to be described. In the former, he embraced the basic tenets of the relativistic quantum field theory in spite of its imperfec-

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tions. In the latter, he took the cue from nature, and asked himself what kind of particle/field should be responsible for the strong nuclear forces. He even tried to kill two birds with one stone, linking the weak interactions with the same hypothetical particle.

In the subsequent development of particle physics for the past fifty years, one may detect in the efforts of theorists two competing modes of approach which are related to the two types of questions just discussed. In this talk I would like to call them the Yukawa mode and the Dirac mode. The Yukawa mode is the pragmatical one of trying to divine what underlies physical phenomena by attentively observing them, using available theoretical concepts and tools at hand. This also includes the building and testing of theories and models. It is the standard way of doing research in all branches of science. In particle physics, the following examples come to my mind:

- Quark
- GUTS (grand unified theories)
- Parton model
- Dual resonance-string model.

The other mode, the Dirac mode, is to invent, so to speak, a new mathematical concept or framework first, and then try to find its relevance in the real world, with the expectation that (in a distorted paraphrasing of Dirac) a mathematically beautiful idea must have been adopted by God. Of course the question of what constitutes a beautiful and relevant idea is where physics begins to become an art.

I think this second mode is unique to physics among the natural sciences, being most akin to the mode practiced by the mathematicians. Particle physics, in particular, has thrived on the interplay of these two modes. Among examples of this second approach, one may cite such concepts as

- Magnetic monopole
- Non-Abelian gauge theory
- Supersymmetry.

On rare occasions, these two modes can become one and the same, as in the cases of the Einstein gravity and the Dirac equation.

§ 2. Evolution of the Lawrence-Yukawa paradigm

The Lawrence-Yukawa paradigm has been, and still is, the dominant mode of research in particle physics. As far as the experimental side is concerned, this will remain so in the foreseeable future, although the big accelerators now seem to be approaching practical limits due to their cost and physical size.

Turning to the theoretical side, a kind of revolution took place in the early 70's when the above mentioned interplay of the two modes began to bear fruit. First of all, the progress in the quantum theory of non-Abelian gauge fields opened up the possibility that gauge fields are at the root of all the forces in nature. The two types of interactions that Yukawa set out to explain in terms of intermediary particles, i.e., the strong and the weak, could now be viewed, together with the classic electromagnetism, as different manifestations of gauge fields, i.e., the color $SU(3)$ and flavor $SU(2) \times U(1)$, acting on the fundamental fermions, i.e., the quarks and leptons. The ensuing grand unification of the three forces, as embodied in the GUTS, immensely appeals to our sense of the unity of natural laws. It is also interesting and satisfying that the magnetic monopole, which was origi-
nally an object of free invention by Dirac, has turned out to be a natural and inevitable consequence of GUTS.

The grand unification, however, is not a complete unification because gravity, the oldest and the most universal of the forces, is not yet included. As the next step, attempts to unify all forces including gravity have led to the revival and modern interpretations of the Kaluza-Klein theories, in which internal symmetries are reflections of the geometry and topology of higher dimensional manifolds. Thus, at least conceptually, there is a natural framework in which a unification of all forces can be envisioned. Yet this program of complete unification still suffers from some defects:

a) Gravity cannot be consistently treated as a quantum field theory. This is similar to the situation with quantum electrodynamics before renormalization theory. However, the problem goes even deeper than that, involving conceptual questions.

b) The program still remains at a phenomenological level as far as the weak interaction is concerned, because it only describes, but does not explain, the irregular and symmetry nonconserving aspects of the weak interaction.

c) Direct tests of the basic ideas can be done only at energies way beyond the reach of present accelerators. There are only a few low energy manifestations.

The last point underscores the peculiar position in which particle physics finds itself at present. There now exists a growing disparity between the capacities of theory and experiment. Theory cannot make precise predictions about phenomena just above the available energies, and accelerators cannot possibly reach the grand unification energies where predictions are clear. This is a rather unfortunate situation. Only if by luck any convincing evidence should turn up about nucleon decay, the situation would change drastically, and we could happily say that theory has leapfrogged many decades of GeV's, and fixed our bearing toward a distant but reassuring star. As of now, however, the original optimistic predictions about nucleon decay have not been confirmed, and again the lengthening time scale for experiment has become a frustrating element as is also true with the case of accelerator development.

Perhaps one should not complain too much about it. Yukawa's meson did not turn out to be just of one kind, but actually have come out in vast numbers. Even completely unexpected new leptons have showed up. It may be that we have grown too self-confident and expecting too much out of theory.

In the meantime, theory and experiment seem to be going their separate ways. Theorists have turned from accelerators to astrophysics and cosmology for guidance and testing, but this is a far less reliable or controllable means than laboratory experiments. In a way we are being forced back to the time when cosmic rays were the primary tool of particle physics.

§ 3. The rise of the Dirac mode

There is, however, yet another trend in theoretical activity which has been going on for some time. It is the rise of paradigms in the Dirac mode, and I would like to address it for a moment. The topics that falls under this category in my mind are supersymmetry and string theory.

a) Supersymmetry paradigm

If non-Abelian gauge theories and monopoles have already found their immediate
physical relevance in the GUTS, such is not yet the case with supersymmetry. It seems a bit of an accident that the appearance of supersymmetry coincided with the progress in gauge theories. Gauge theories are a generalization of known physical theories, but supersymmetry is not. The situation is somewhat similar to that of the Dirac equation. In the latter case, however, it found immediate relevance.

Theoretically, supersymmetry has some very appealing features, like improved ultraviolet behavior. Perhaps more importantly, it can admit particles of all spins, from Higgs boson to graviton, to be as equals, a feat of ultimate unification. Unfortunately, the way fermions and bosons are organized in supersymmetric theories does not seem to correspond to the patterns of known fermions and bosons. So supersymmetry simply adds more unknown partners to the known ones without explaining the latter.

Unlike gauge theory, supersymmetry is not based on a conceptually simple principle. In fact it is not clear what the principle is. Without known examples, and without a clear physical principle behind it, supersymmetry by itself does not look much different from other mathematical constructs like parastatistics.

b) String paradigm

String theory has a solid phenomenological origin, and is not a result of free invention. In hadron physics where it originated, it has come to be regarded as a phenomenological substitute for quantum chromodynamics, just as the Ginzburg-Landau theory is a phenomenological substitute for the Bardeen-Cooper-Schrieffer theory of superconductivity.

But somehow string theory has acquired a life of its own. By combining the three formal ideas represented by the string, supersymmetry and Kaluza-Klein theories in a unique way, and applying them to the most speculative and inaccessible realm of physics, the recent superstring theories have suddenly found themselves serious candidates for an ultimate theory of the world. In the very least, it seems to offer the possibility of a finite quantum theory of gravity along with all other forces and particles.

Superstring theory presents a utopian vision of the world. The only big question is whether it is a vision of the real world or not. So far, the vision is set only at the asymptopia of Planck energies. One cannot yet say with confidence that our low energy world and the world of superstrings live in the same connected manifold. Whatever the predictive power of the superstring theory may turn out to be, there is every reason for us to explore experimentally the physics in the TeV range where something must surely happen to the weak interaction but one does not know exactly what to expect.

§ 4. Speculative comments

So far I have engaged only in philosophical characterizations of the ongoing trends of particle physics. I would like now to present a few ideas of my own. My intention is to explore alternative ways, as different as possible from the standard ones, to look at some unsolved problems (in the perverse hope that I may be proven wrong!).

My primary interest in this regard concerns the weak interaction in general, and the question of fermion generations and mass spectra in particular. I am struck by the fact that among the four types of interactions, the weak interaction alone is the one that does not respect symmetries. Under the current thought, the mass spectra of quarks and leptons are intimately related to their weak interactions. It is these seemingly capricious
mass spectra that make the world look so complicated. Without the problem of mass, the
world might be much simpler, but at the same time very boring.

Physicists engaged in model building take pains to conform to the real world without
questioning the latter. It is instructive, however, to reflect on how the nature of the real
world, down to the existence of life itself, may be critically dependent on some very subtle
properties of the Kobayashi-Maskawa fermion mass matrix. If a model builder were not
concerned about fitting the real world too well, but just followed his natural logic, the
predicted world probably would be vastly simpler than the real one. Perhaps he would
first assume the mass matrix to be diagonal, in which case each generation would be
stable, and there would exist many exotic forms of matter. Even if he took into account
the possibility of generation mixing and worked out other fine details, would he correctly
conclude that the up quark is lighter than the down quark, in such a way that the
neutron-proton mass difference comes out greater than the electron mass so that free
neutrons decay? Without this, the world we know would not exist and the human beings
would not be around to pose such questions.

What I am driving at is the question whether or not our world is really predictable
down to its minute and subtle details. As pointed out above, the most serious difficulties
come from the weak interaction sector. A natural answer to the existence of fermion
generations with complex spectra would be that the fermions are composite objects with
substructure. Yet a naive notion of compositeness does not seem to apply here, because
a) the mass spectra are too irregular and too sparse, and b) there are no signs of a
substructure; in fact the good agreement of the Weinberg-Salam theory with experiment
and the absence of processes like $\mu \rightarrow e\gamma$ decay cannot easily be reconciled with composite-
ness.

So let me for a moment try to be as radical as possible, and challenge the notion of
the laws of physics in the sense commonly understood by physicists, namely that there is
a unique Lagrangian from which all the laws of physics are derived and the properties of
the physical world determined. This could be done in various different contexts. For
example, one could say that one really has to integrate over all possible theories of the
world according to the quantum mechanical principle. Actually this may not be much
different from what we usually do, if a particular theory, the "right" one, has a dominant
probability among all theories.

In a more serious vein, one could ask whether the laws of physics are intimately bound
up with the evolution of the universe, influenced not only by the initial conditions, but also
by the subsequent evolutionary processes themselves. In a way I am suggesting the
biological evolution as a possible model for physical evolution.

One would have to be more specific, however, so let me entertain the idea that the term
"generation" means more than just an analogy. Is it at all possible that the generations
of quarks and leptons have "evolved" one after another in some sense, that each genera-
tion is "born", so to speak, at the corresponding energy (or length) scale of an expanding
universe, its properties being influenced, but not necessarily deterministically fixed, by
what already exists?

Biological evolution apparently is made possible by the vast degrees of freedom
residing in complex molecules. If translated to particle physics, this might again bring
back the compositeness issue. Are lower mass generations more complex than the higher
ones? This is hardly likely although the opposite might be true. So what I should mean
would be that the constants like mass are really dynamical quantities that were selected, with some degree of chanciness, from among other possibilities in the course of the universal evolution.

We do not know how many generations really exist and why. But let us consider, for example, the following hypothesis. Fermions of one generation with a characteristic mass \( m \) will exist in abundance during the cosmological expansion if \( m \) is less than the temperature. Assume that these fermions will beta decay by creating a new generation with lower mass if the decay rate is higher than the rate of expansion at that moment.

The beta decay rate goes like

\[
\sim m^5/M_W^4,
\]

where \( M_W \) is the \( W \) boson mass. On the other hand, the expansion rate of the universe at temperature \( T(\sim m) \) goes like

\[
\sim T^2/M_P,
\]

where \( M_P \) is the Planck mass. As the universe expands and the temperature cools down, the decay rate will decrease more rapidly than the expansion rate. These two rates become equal when \( T \) is of the order of a few MeV, which is the mass scale of the lowest and last generation. It may not be complete nonsense to read some significance into it. (The above condition is the same as that which applies to general decoupling of weak processes out of thermal equilibrium. Incidentally, if the electron decayed to an even lower generation, its lifetime should be about a week.)

I would like to end my talk with a less drastic remark than the one just given. It concerns the problem of supersymmetry again. The relativistic supersymmetry of Wess and Zumino has not yet found any direct experimental support. In the meantime, however, certain kinds of supersymmetry have turned out to be useful concepts in certain problems of quantum mechanics and statistical physics. But the real physical meaning underlying supersymmetry still remains unclear.

One of the most interesting cases of apparent supersymmetry occurs in nuclear physics. As has been analyzed by Iachello and collaborators, a group of nuclei having even or odd mass numbers form an approximate supermultiplet with regard to their low energy spectra. Recently I have attempted to attribute this to a general feature of the BCS pairing mechanism, which certainly applies to nuclear physics. Whether it is in fact the mechanism behind the Iachello supersymmetry or not, the BCS theory leads to rather simple relations among low energy bosonic and fermionic spectra. These relations have been experimentally confirmed in superconductors and superfluid helium 3. For example, the analogs of the pion, quark, and \( \sigma \) meson in a superconductor have masses in the ratio 0:1:2 (in the absence of the Coulomb interaction). In terms of the effective theory (\( \sigma \) model) of Ginzburg-Landau and of Gell-Mann-Levy, it means that the Yukawa and quartic self-couplings of the bosonic fields are simply related. A similar result is obtained when the formula is applied to the nuclear case.

The question is: In what sense does the BCS theory have a hidden and approximate supersymmetry? As it turns out, it is possible to express the static (non-kinetic) part of the effective Hamiltonian for a superconductor as a product of fermionic operators \( Q \) and \( Q^\dagger \) as in supersymmetric quantum mechanics:
\[ Q = \pi^* \psi_{ud} - i (\phi \phi^* - \eta^2) \phi_{dn}, \quad \bar{Q} = \int Q dv, \]

\[ H = \{ \bar{Q}, Q^* \} \]

\[ = \int [\pi \pi^* + (\phi \phi^* - \eta^2)^2 + \psi_{ud} \psi_{dn} \phi^* + \text{h.c.}] dv, \]

where the \( \phi^* \)'s are the spin up and spin down electron fields, \( \phi \) and \( \pi^* \) are a bosonic field and its canonical conjugate field representing electron pairs. (\( Q \) and \( Q^* \) carry a definite charge unlike quasi-particle fields.)

The difference from the case of rigorous supersymmetry lies in the fact that \( Q \) and \( Q^* \) do not commute with \( H \) because \( Q^2 \) and \( Q^{12} \neq 0 \). But one may say that the latter are effectively proportional to \( \langle \phi \rangle \), and thus the spontaneous breaking of the \( U(1) \) (charge) symmetry also breaks a supersymmetry between fermions and bosons as is reflected in their mass relations.

In more general cases of the BCS mechanism, one can let the fields become multicomponent:

\[ Q = \pi^* \phi - i V(\phi) \phi^*, \]

\[ H = \{ \bar{Q}, Q^* \} \]

\[ = \int [\text{Tr}(\pi \pi^* + VV^*) + [\phi, V'\phi]/2 + \text{h.c.}] dv, \]

\[ V' = \partial V/\partial \phi. \]

Here the bosonic fields are matrices acting on the fermionic fields. These formulas give the rest spectra of bosons and fermions for the examples of helium and nuclear physics mentioned above.

It is not yet clear why this formulation of the BCS theory works. But one would be tempted to apply it to the problem of dynamical mass generation for the fundamental fermions, assuming that it is due to a similar mechanism. In the simplest analogy, each fermion would be accompanied by a Higgs partner of comparable mass, and their coupling would not be expected to be very weak. This certainly does not seem correct. More likely are the technicolor type theories, in which case the Higgs and some heavy fermions form partners, but this would not by itself shed light on the riddle of the mass spectra of the known fermions.

References