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August 1974

NUCLEAR PHYSICS IN A LARGER PERSPECTIVE

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I. What is nuclear physics?

First of all I shall like to say a few words on what is nuclear physics. In the popular mind the present age is the Nuclear Age. This impression has been to a large extent contributed by the demonstrated destructive power of the so called "Atom Bomb" and the much fanfare of claims regarding the "limitless" source of energy from controlled fission and fusion processes. From a technical viewpoint, Nuclear Physics proper covers only a small part of the developments in modern physics. Considering the state of poor understanding of nuclear phenomena it is difficult to characterise nuclear physics: the only common denominator being that it deals with nuclei.

But a variety of problems in electrodynamics, solid liquid and gaseous states of matter could involve some considerations of the nucleus. Hence it would be more appropriate to <u>define nuclear physics as dealing</u> with <u>those phenomena which involve active interaction between nucleons and nuclei and which may result in change in the state of the nuclei in interaction</u>. For instance in the case of liquid He^4 its' statistics is determined by the nuclear spin; but this is not an active interaction but rather "passive" or "kinematic" effect and hence not part of nuclear physics per se.

Within the above definition nuclear physics was born, so to say, in the discovery by Becquerel of Radioactivity in 1896. May I seek your indulgence to recall that three types of rays were discovered: α-rays, β-rays and γ-rays. The qualitative explanation of α-decay phenomena by Gamow set the tune for the applicability of Quantum theory to the study of nuclear phenomena. The γ-rays turned out to be electromagnetic waves. The success of quantum theory in the case of electromagnetic interactions (in molecules, atoms and nuclei) encouraged Fermi to give an anologous formulation for the phenomena involving β-decay. It was soon realised that β-decay belongs to a very wide class of phenomena which are collectively characterised as weak interactions. It is a surprising fact that the Fermi type formulation involving the motion of currents is found to be always possible for describing these phenomena. Unfortunately, however, unlike the electromagnetic theory no systematic procedure has yet been discovered to extract finite results for such a field theory. The forces which keep the nucleus together may roughly be characterised as strong interactions. The application of quantum theory has been even much less successful here. Consequently, the understanding of the fundamentals of nuclear theory is non-existant in this larger perspective. As a result, the subject has been practically split into two subjects.

(1) Nuclear Physics. This deals with the structure of a nucleus and with phenomena involving low energy nuclear physics. It does not concern itself with fundamental questions but is essentially confined to determine the effective interaction. It is this which is popularly called nuclear physics.

(2) The High Energy or Elementary Particle Physics: This deals with the study of phenomena involving particles responsible for nuclear forces in their nascent state. All the fundamental questions of nuclear physics form the subject matter here.

II. Problems and scope of Nuclear Theory

What are the problems and scope of nuclear physics in the narrow sense as defined above. Since there is no basic theory of nuclear physics, one has to set up models based on classical experience to fit the data, assuming the basic background structure to be quantum theory. There are two principal studies involved. (1) Interaction between "free nucleons" (2) the interaction between nucleons in nuclei. When one talks of interaction one is always looking for an effective interaction. To find it we need experimental data. If we had all the data we want it may be possible to determine empirically the effective interaction completely. Though a large amount of data is available at present, it is still not large enough for a complete determination of the interaction. However considerable progress has been made. The development of shell model of the nucleus is an excellent example of the painstaking collection and study of nuclear data which showed that in spite of strong initial objections it is nevertheless possible to describe the <u>structure</u> of a nucleus in terms of a shell model if one assumes a strong enough spin-orbit coupling. A bye-product of these studies has been the first extensive use of various "internal (as against <u>geometric</u> symmetry groups) symmetry groups" such as SU_2, SU_3 and SU_4 in nuclear physics much before they became fashionable in elementary particle theory. There are of course other nuclear structure models which are, however, used to explain only a particular class of phenomena. The scattering data on free nucleons and between nucleons and nucleus and its theoretical study forms another important branch of study called <u>Nuclear Reactions</u>. In the world of ideas it is relevant to mention here the tremendous impact that the Bohr's idea of the compound nucleus had on the developments of nuclear reaction theory. A close look at all these developments show that there is a striking parallel between (what we call) <u>Reactions</u> on the one hand and <u>Structure</u> (Shell Model) on the other.

However, in spite of all these "successes" the scene in nuclear physics is still far from satisfactory. Firstly, in the absence of any basic theory the various models, however successful they are in a given local setting, are at best only a stop gap arrangement. Secondly, even at the level of what is usually called nuclear theory, the quality of agreement between theory and experiment is unsatisfactory.

At this point it is useful to add that in high energy physics, the situation is not basically different. In the absence of a basic theory the phenomenological theories and models are the usual theoretical approaches. Each of these models however is successful in only a limited area. One may therefore question the very efforts made in developing such models to fit the data. On the other hand we recall that the birth of almost every physical theory has been preceded by a long trial of data fitting. For instance, Newtonian mechanics (experiments of Galileo, Huygens, Newton and others), Newtonian Gravitation (work of Kepler, Galileo and others before them), Maxwell's electromagnetic theory (discovery of Coulomb's law; the laws of Ampere and Faraday), Special relativity (various experiments on electrodynamics of moving bodies and attmpts to fit the data) and Quantum theory (discovered in trying to fit data on spectral lines of atoms and molecules). Apart from this argument based on historical developments in physics let me add that these phenomenalogical and model making studies have also been of immediate application. I have in mind here, the application of models and methods developed in these studies to other situations elsewhere in physics and engineering.

The case of the development of quantum theory is of particular interest to us. As already mentioned quantum mechanics was first formulated in the study of electromagnetic phenomena in atoms and molecules. The understanding of quantum electrodynamics has also enabled one to make considerable progress in the understanding of other nuclear phenomena by using electromagnetic interaction as a probe. A certain superficial anology of weak interaction "theory" with the electromagnetic theory is also perhaps responsible for most of the progress in the weak interaction theory. Any other advance in the understanding of weak and strong interaction physics is mainly phenomenological. It is therefore not possible to rule out that Quantum Theory is strictly applicable only to electromagnetic processes and that the nuclear phenomena are outside the scope of Quantum Mechanics. However in the absence of availability of any other tangible mechanics, quantum mechanics is the best we have. Hence within the scope of quantum theory and Relativity one would like to know if it is possible to predict some general features of a nuclear theory from some qualitative considerations. In the following we attmpt such an analysis.

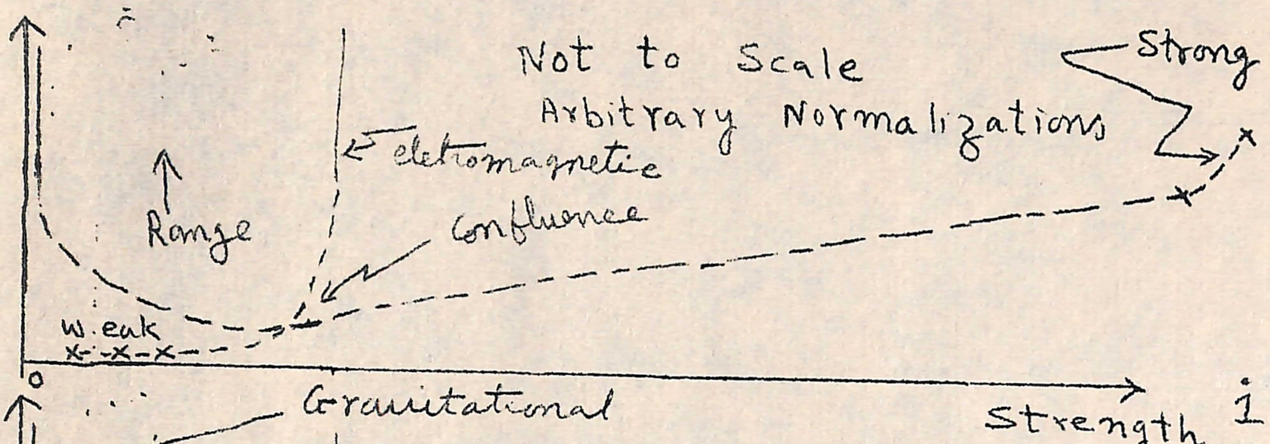
III. Strength-Range Relationship

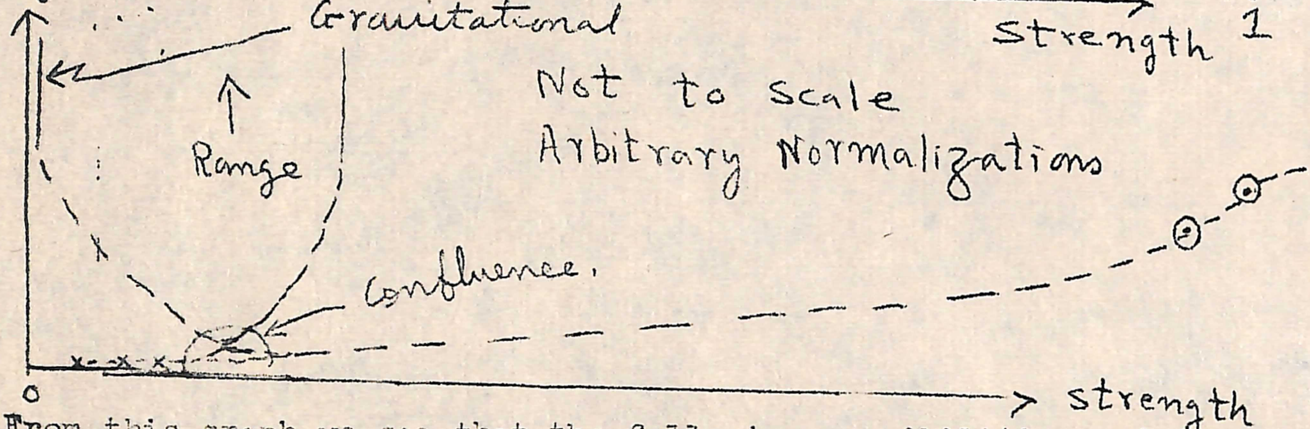
If we consider various interactions in nature, these can be roughly classified in terms of two concepts, viz. Strength and Range of the interaction as indicated in the following table. We must hasten to add that there are several other distinguishing features of these interactions which permit this classification.

	Strength	Range	Name of the interaction
1.	Very small (precisely known)	Infinite	Gravitational
2.	Small (values in a certain range)	Very short possibly zero (values in a certain range)	Weak
3.	Large (precisely known)	Infinite	Electromagnetic
4.	Very large (values in a certain range)	Short (values in a certain range)	Strong

It is clear from this table that if [illegible] range is infinite, the strength is a precisely defined number and vice versa. On the other hand if the values of strength of a given type of interaction lie in a certain interval then so do the values of the Range; this is the case for all short range interactions.

A close study of electromagnetic and gravitation theories reveals the role of their static fields which essentially determine their infinite Range and therefore their Strength. We conclude that in the case of short range interactions there is no clear distinction between static and dynamic processes, but the two are interlinked in the sense that a theory based on static interaction even in the most favourable case can atmost only be a rough approximation. The dynamic nature of the interaction only implies that there are several fields involved simultaneously in these interactions as is evident from a range of values for Strength in case of short range interactions. For this reason it is all the more important to study the relationship between Strength and Range for short range interactions using the boundary condition, that as range $\longrightarrow \infty$ strength converges to a well defined number. The following qualitative graphs[1] gives a rough picture of Strength-Range relations.





From this graph we see that the following possibilities exist

(1) Weak and strong interaction trajectories have separate asymptotic limits; these being respectively electromagnetic and gravitational coupling constants. In this case we can expect that in an overall theoretical structure there will be substructures of combined "weak and electromagnetic theory" on the one hand and "strong and gravitation theory" on the other; the intersection of the two graphs would provide the point of contact.

(2) Present evidence indicates that the Range of weak interactions is in all probability exactly zero. In this case there is a strong possibility that there is a single trajectory (with branches)

on which all the interactions lie. In this connection we note that to-date all attempts to write only electromagnetism and gravitation have failed; hence any link between them has to be via the other interactions viz. short range interactions. Thus for instance heavy spin one particles of the same quantum numbers as the photon couple the electromagnetic field and similarly the heavy spin two particle could couple to the gravitation!

At this point it is necessary to emphasise that for the purpose of our discussion it is not necessary that every point on the strength-Range graph should be realisable in nature; in fact the distinction between various types of interactions is not possible in the first place if that was the case. Moreover it appears that for the case of weak processes there are only discrete points but for strong processes there is in all probability a limit point. This would mean that there are infinitely many particles involved in a complete description of strong processes.

It is our hope and conjecture that a more concentrated study will show that gravitational and electromagnetic interaction coupling constants arise from the strength-Range relation for strong and weak interactions roughly in the manner indicated above (i.e. in the infinite Range limit). In further support of this view-point we present the following considerations.

Recall that in analysis of the concept of time and the related concept of simultaneity one is ultimately led to conclude with Einstein that since electromagnetic waves enter in a natural way in prescribing synchronization between clocks, certain properties of these waves must play an active role in the definition of these concepts. This accounts for the leading role assigned to the velocity of light in special relativity. In fact arguments along these lines led Einstein to the Special and General theories of Relativity as a natural completion of the corresponding ideas of Newtonian mechanics and gravitation. A similar situation exists in the theory of elementary particles. All short range interactions both strong and weak are observable only in terms of electromagnetic and gravitational phenomena, in the sense that the observation and analysis of the experiments involving strong and weak interactions invariably involve electromagnetic and possibly also gravitational phenomenon. Working along this line of thought we conclude that electromagnetic and gravitational phenomena play an important role in the theories of Weak and Strong interactions.

The Strength-Range relations for short range interactions have a further significance independent of gravitation and electromagnetism. For a given coupling constant for strong interactions we can define a certain 'Range' number, say, ℓ_1; by this we mean that the interaction takes place in the range 0 to ℓ_1 and effectively vanishes for distances greater than ℓ_1. It is now possible to do Fourier analysis on $[0, \ell_1]$; discrete numbers which thus arise we call n_{ℓ_1}. In the same fashion other coupling constants give rise to further numbers $n_{\ell_2}, n_{\ell_3}, \ldots$ In a basic theory of fundamental particles if we thus start with say 3 (this is a necessary minimum) basic coupling constants and their corresponding Ranges it is possible to build up a discrete set of secondary coupling constants (and the corresponding Ranges) by a linear superposition; such a set would clearly have a limit point. It is quite possible that quark and parton models arise just in this manner. Detailed study is here called for.

IV. Space-time dimension

> It is probable that the 3-fold dimensionality of space is a consequence of the law according to which the forces of substances act on each other
>
> Emanuel Kant[2]

A puzzling aspect of any physical theory much taken for granted is the space-time dimensionality. We shall presently show that the dimensionality actually found in nature[3] has much to do with certain discrete and internal symmetries of elementary particle theory. Let the space-time be of d dimensions and pseudo-Euclidean of signature ± (d-2); the spatial dimension is then (d-1). If d is odd, (d-1) is even; hence spatial inversion in this case is a continuous symmetry and not a discrete operation. Now it is a fact of life that right polarized and left polarized light waves which are mirror images of each other are physically distinguishable. We note parenthetically that the distinguishability between left and right is in a measure responsible for the very existence of life since this distinction plays no inconsiderable rôle in biological, biophysical and chemico-physical phenomena[4]. If it were possible to convert right polarized and left polarized waves into each other by a mere rotation (as would be the case if space was even dimensional) then there would exist no enantiomorphs and no enzymatic action. From this viewpoint we are led to conclude that asymmetry in nature, as observed in the biological world is a necessary condition for life as is the odd dimensionality of space with which it is interlinked.

Returning to the role of mirror symmetry in particle theory, we note that even though right and left handed waves are distinct, it is possible to take their linear superpositions to obtain plane polarized and elliptically polarized waves which again exist as "single" entities. On the other hand if we take the corresponding spin group (covering group of Euclidean motions) of the space-time symmetry, we find that its representations for the zero mass case do not even permit a linear superposition if the space is odd dimensional. The existence of neutrinos and antineutrinos is thus an inevitable consequence of the odd dimensionality of space (and even dimension of space-time) which in turn is the sine qua non for the very concept of parity and hence also of its violation.

We saw in the above that two states of opposite parity for light waves are superpasable, but this is not the case for neutrinos. One distinguishes these two cases by saying that right and left polarized waves are related by ordinary, or $\mathcal{P}$ parity, whereas neutrinos and antineutrinos are related by generalized or $\mathcal{C}\mathcal{P}$-parity. In the case of light waves $\mathcal{C}$ has the interpretation that there are two types of charges, positive and negative and the electromagnetic waves (whether real or virtual) mediate interactions between them; of this we already know from the electromagnetic theory.

If the space is odd dimensional, clearly the space-time is even dimensional. Since space-time is pseudo-Euclidean, of signature ± (d-2), the inversion of the sign of all the d coordinates is not possible as was the case for Euclidean spaces. However the operation of changing the sign of all the d(=even) coordinates has determinant +1, as in the case of rotations ! This presents interesting possibilities. To start with we generalize the $\mathcal{C}\mathcal{P}$ operation by defining a space-time inversion operator called "Strong Reflection" [5,6] which has the obvious form $\theta = \mathcal{C}\mathcal{P}\mathcal{T}$ where T stands for "Time Reversal".

Since θ has determinant $+1$, we expect that there is an extension of the isotropy group of space-time (viz. the homogeneous Lorentz group), such that θ is continuously connected to the identity in the extended group (It is clear that this is not possible if d is odd, for then the determinant of θ is -1). The complex Lorentz group gives just this extension. We have shown elsewhere[7] that the maximal compact subgroup of the complex Lorentz group gives precisely the group in which θ is continuously connected to the identity only if d=4. In this case the group in which θ is continuously connected to the identity is $SU_2 \times SU_2$. This may be considered as an argument in favour of space-time dimensionality of four[3]. On the other hand one could also conclude that given a pseudo-Euclidean space-time with d=4, any internal symmetry group must contain $SU_2 \otimes SU_2$ as a subgroup; the simplest possibilities thus are $SU_3 \otimes SU_3$ or SU_4.

In the context of this conclusion we note the following. For the Dirac equation the operation θ involves a linear transformation by γ_5; for the case of vanishing mass one obtains the so-called γ_5-symmetry which gives rise to the characteristic doubling of leptons. In our analysis this doubling is of more general nature and would also extend to strongly interacting particles. We note, that similar conclusion also obtains from considerations of an entirely different nature in the recent work on broken space-time dependent internal symmetries[3].

Summary: In the first two sections we discuss the place of Nuclear Physics vis-a-vis the developments in physics of the last half century, It is concluded that the basis of Nuclear theory can be clarified only in the larger context of physics of all matter and energy. In this connection two general lines of thought are developed using the (1) concept of strength-Range relationship for various interactions; and (2) space-time dimensionality and discrete symmetries.

References

1. The following references contain useful data for drawing such graphs. The present graph however is purely qualitative.
    - a. G.Ebel, H.Pilkuhn, Nuclear Physics B.17 (1970), 1 (compilation of coupling constants and low energy parameters)
    - b. Mary E.M.Hogan, Thesis Florida State University, Tallahassee (Uses SU_3 x SU_3 Chiral Lagrangian model and determines several "scattering lengths" and coupling constants)
    - c. Gribov, et. al. Zh. Eksper. teor. Fiz (USSR) 41 (1961) 619; Phys. Rev. Letts. 11 (1963) 55-58 (Limits on coupling constants)

It is desirable to collect more such data and make a qualitative study to compare various models.

2. *Gedanken von der Wahren Schatzung der lebendigen Krafte, secs.* 10-11. English translation (Thoughts on the true Estimation of Living Forces) in John Handyside, *Kant's Inaugural Dissertation And Early Writings on Space*, (Chicago, 1929)

3. For other arguments in favour of 4-dimensional space-time, see K.H.Mariwalla, J.Math.Phys. 12 (1971) 96.

4. For a discussion of assymmetry in nature referred to here see for example, K.H.Mariwalla, Ph.D. Thesis (1963) University of Georgia (U.S.A.), Introduction. Glucose, Sucrose and Racemic Compounds (known since Louis Pasteur-1848) are well known enantiomorphic compounds. The connection with biophysical phenomena arises via enzymatic action. We note that to seperate two enantioforms one either requires a physical process (seperation by hand (!) or by use of circularly polarized light) or enzymatic action.

5. The expression strong reflection is due to W.Pauli in Niels Bohr and the Development of Physics. Editor W.Pauli, Pergamon Press, N.Y.

6. For the definition and representation of discrete operators in Quantum Theory of free fields see K.H.Mariwalla, Revs. Mod. Phys. 34 (1962) 215. For their representations and general properties in Quantum Theory, see ref.7.

7. K.H.Mariwalla, J. Math. Phys. 7 (1966) 114. In this reference we actually consider only d=4; in ref.3 some of the considerations here are utilised in a wider perspective for arbitrary even dimensionality.

8. Early ideas on this were given by F.A.Kaempffer, Can. J. Phys. 32 (1954) 259. A more concrete model involving broken symmetry of the vaccum was suggested in the work of Y.Nambu and G-Jona-Lasino, Phys. Rev. 124 (1961) 246 and of W.Heisenberg, Z.Naturo Forsch 14 (1959) 441. But the clear concept of association of a particle with a broken symmetry first arose in the work of J.Goldstone, Nuo. Cim. 19 (1964) 154. The Goldstone-particle here arises as a mass zero particle. If one assumes that internal symmetry generators are space-time dependent one finds that during breaking of the symmetry an originally zero mass particle develops mass: P.W.Higgs, Phys. Letts. 12 (1964) 132; T.W.B.Kibble, Phys. Rev. 155 (1967) 1554. In work of the present author on projective cosmology the broken symmetry gives rise to a space-like particle. Proc. Conf. on Cosmology, Gravitation and application to particle theory (1971); Matscience Report 76 (1973)