Historical Perspective on the Impedance Approach to Quantum Field Theory

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The absence of impedances from the Standard Model is most remarkable. Impedance is a fundamental concept, of universal validity. Impedances govern the flow of energy. In particular, the coupling of the photon to matter happens in the near field. The absence of the photon near field impedance in photon-electron interactions is the most basic and profound example of this remarkable circumstance, sitting unnoticed in the foundation of quantum electrodynamics. One cannot obtain a complete understanding of such interactions without examining the role of impedances. How this essential principle escaped notice in the development of quantum field theory is outlined, and consequences of its inclusion in our present understanding are explored.

INTRODUCTION

Given the practical everyday utility of the impedance concept in technical applications, it is not surprising that one finds the most helpful historical introductions and expositions not in the academic literature, but rather in that of technologically advanced industries, where proper application of the concept is essential for economic success. The reader is encouraged to consult a sampling of that literature[1–4] for straightforward presentations of basic impedance concepts.

This inadvertent divorce of the theoretical from the practical has had profound consequences for quantum field theory (QFT), where the Hamiltonian and Lagrangian formalisms are focused upon the conservation of energy, rather upon than that which governs its flow, the impedances.

The inevitable reconciliation of practical and theoretical, the incorporation of impedances into the foundations of quantum theory, is potentially paradigm-shifting in condensed matter, gravitation, and particle physics, as well as in the most esoteric of the present pursuits in theoretical physics, where it is forgotten that vibrating strings have characteristic impedances[5].

The most rudimentary example can be found at the foundation of quantum electrodynamics (QED), in the photon-electron interaction. The formidable breadth of the crack through which the impedance concept has fallen becomes apparent when one considers that the near field photon impedances[6] shown in figure 1 cannot be found in the physics textbooks of electricity and magnetism[7–12], QED[13–23] (although Feynman[24] does mention impedances in the context of boundary conditions of the one-dimensional crystal, and in the context of influence functionals), or QFT[25–30].

While common knowledge in the engineering community, it is **most remarkable and significant** that what governs the flow of energy in photon-electron interactions is explicitly absent from the formal education of the PhD physicist.

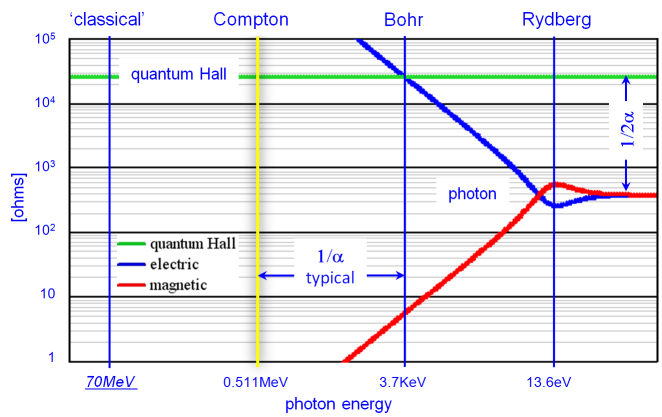

FIG. 1. Far and near field 13.6eV photon and scale invariant electron impedances as a function of spatial scale as defined by photon energy. The role of the fine structure constant α is prominent in the figure.

IMPEDANCES, CLASSICAL AND QUANTUM

In simple terms, impedance may be defined as a measure of the amplitude and phase of opposition to the flow of a current. Zeldovich[31] defines impedance in terms perhaps more useful to the theoretician, as a measure of the ellipticity of phase space trajectories, then goes on to normalize the conjugate variables (p,x) by the impedance, which permits him to calculate impedance-based quantum creation and annihilation operators.

Impedances can be mechanical or electromagnetic, classical or quantum, fermionic or bosonic, geometric or topological, scale-dependent or scale-invariant.

Geometric impedances are scale dependent. Topological impedances (quantum Hall, chiral, centrifugal, Coriolis, three body,...) are scale invariant. The various impedances are one or the other - either scale dependent, or scale invariant. The lone exception is the photon, which has both scale dependent near field and scale invariant far field impedances.

Impedances can be classical or quantum. What distin-

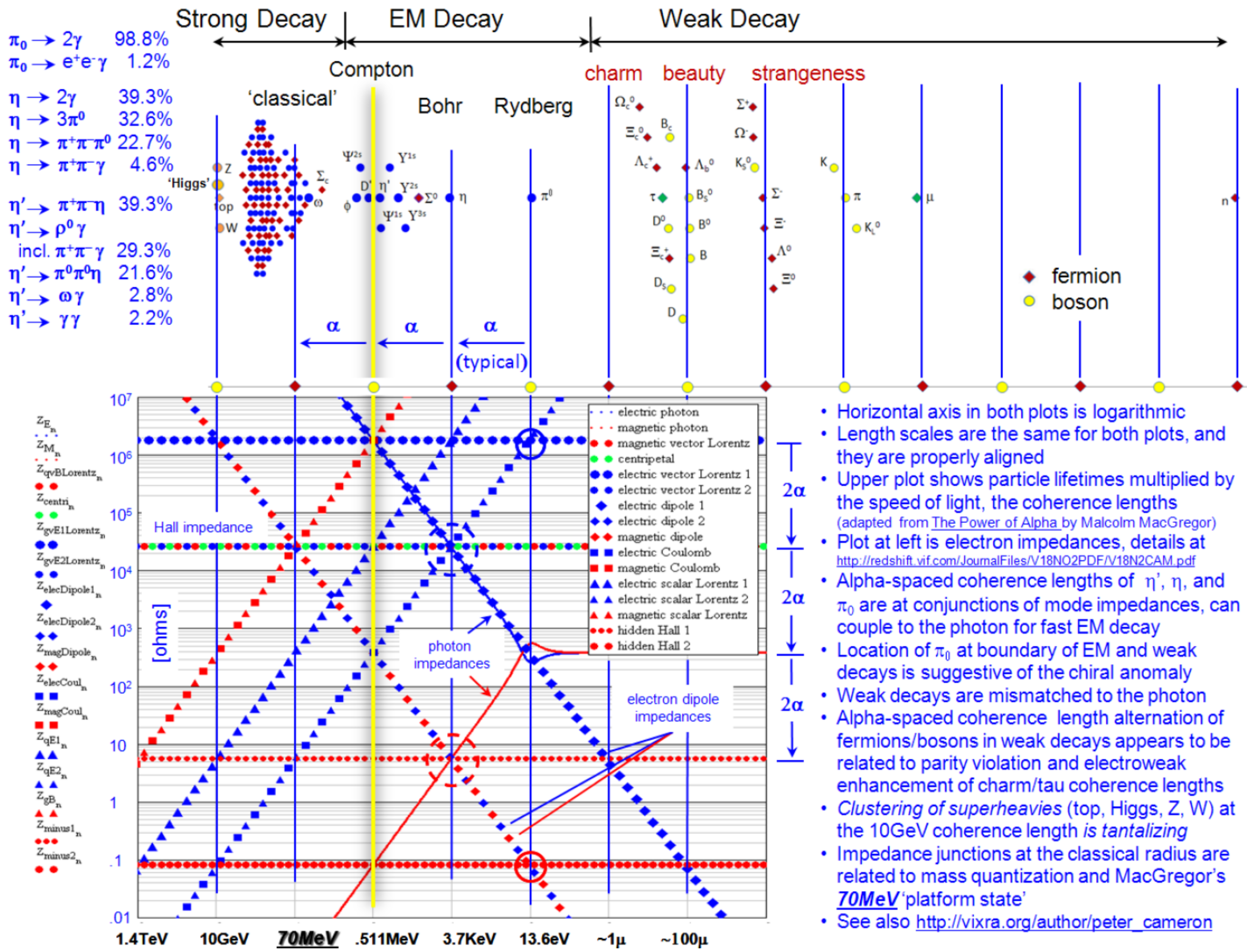

FIG. 2. A composite of 13.6eV photon impedances and a variety of background independent electron impedances[38], measured branching ratios of the π^0, η, and η', the four fundamental quantum lengths shown in fig.1, and the coherence lengths of the unstable particles.[39–41]

guishes the two is the existence of a fundamental length scale, the quantization length. The remainder of this note will focus on quantum impedances defined at the electron Compton wavelength, as highlighted in figure 2. For classical impedances, the reader is again encouraged to consult the references cited in the introduction to this note[1–4].

The quantum impedances found in the canonical literature are limited to the photon and the quantum Hall impedance of the electron. The scale invariant quantum Hall impedance is associated with the Lorentz force, which is perpendicular to the direction of motion and can do no work, can only communicate quantum phase.

Scale-invariant impedances are associated with inverse square potentials[32–36], and in the literature appear most frequently in discussions of anomalies. The phase-only character of inverse square potentials, the incapacity to do work, is emphasized in the case of the centrifugal potential of the free Schroedinger particle by Holstein[34]. The unbroken symmetry is scale invariance.

Quantum impedances can be defined for all quantum potentials and forces, and in particular for those of the electron[37] in the photon-electron interaction. Defining a quantization length has significant consequences, as can be seen from figure 2.

- The low and high energy impedance mismatches of the scale dependent modes that communicate energy provide natural cutoffs. The impedance approach is finite in the absence of renormalization.
- Looking not at what is excluded by these natural cutoffs, but rather at what remains in the middle, the impedance mismatches as one moves away from the quantization length provide a natural confinement mechanism for the coupled modes that define a given particle.

The impedance approach is not only naturally finite, but also naturally gauge invariant. Complex impedances - inductance and capacitance - shift phases. Complex quantum impedance shifts quantum phase, not a single measurement observable. In the Standard Model the phase coherence that distinguishes quantum systems from classical (as required by gauge invariance) is maintained by the artifice of the covariant derivative. In the impedance approach one need only account for the phase shifts introduced by the impedances.

As a consequence of the natural finiteness and gauge invariance, there are no anomalies in the impedance approach[42].

THE MODEL

Given a quantization length, what does one quantize? Restricting the possible fields to electromagnetic only, starting with full symmetry between electric and magnetic, and taking only the simplest topologies needed for an arguably realistic model, we have

- quantization of magnetic and electric flux, charge, and dipole moment
- three topologies - flux quantum (no singularity), monopole (one singularity), and dipole (two)
- confinement to a fundamental length
- the photon

What is shown in the impedance plot of figure 2 are calculated coupling impedances of the interactions between these three topologies[37, 38].

QUANTUM IMPEDANCE HISTORY

If impedances are in fact a useful and powerful tool (as further explicated later in this note), how is it that they are not already present in the Standard Model?

One might suggest that the absence is simply an historical accident, a consequence of the order in which the experimentalists revealed the relevant phenomena. The scaffolding of QFT has been erected on experimental discoveries of the first half of the twentieth century, on the the foundation of QED, which was set long before the discovery of impedance quantization.

The 1980 discovery[43] of a new fundamental constant of nature, the Nobel Prize discovery of exact impedance quantization in the quantum Hall effect, was greatly facilitated by scale invariance. This classically peculiar impedance is topological, the measured impedance being independent of the size or shape of the Hall bar. Prior to that discovery, impedance quantization was more implied than explicit in the literature[44–51]. Early mentions include the 1955 paper of Jackson and Yovits[44] and the 1957 paper of Landauer[45].

Bjorken was perhaps not familiar with their work when writing his 1959 thesis[46]. In that thesis is an approach summarized[47] as "...an analogy between Feynman diagrams and electrical circuits, with Feynman parameters playing the role of *resistance*, external momenta as current sources, and coordinate differences as voltage drops. Some of that found its way into section 18.4 of..." the canonical text[48]. As presented there, the units of the Feynman parameter are [sec/kg], the units of mechanical *conductance*[5].

It is not difficult to understand what led Bjorken astray, as well as those who have made more recent similar attempts[51–54]. The units of mechanical impedance are [kg/sec]. One would think that more [kg/sec] would mean more mass flow. However, the physical reality is more [kg/sec] means more impedance and *less* mass flow. This is one of many inter-related mechanical, electromagnetic, and topological paradoxes[56] to be found in the SI system of units[55].

With the confusion that resulted from misinterpreting conductance as resistance, and more importantly lacking the concept of quantized impedance[43], the anticipated intuitive advantage of the circuit analogy[48] was lost and the possibility of the jump from a well-considered analogy to a photon-electron impedance model was not realized at that time.

Like the first Rochester Conference on Coherence and Quantum Optics in 1960, the 1963 paper/thesis by Vernon and Feynman[49] on the "Interaction of Systems" was motivated by the invention of the maser. It is a particularly suggestive combination of the languages of the electrical engineer and the physicist. The authors devoted a thesis to the concepts needed for impedance matching to the maser. However, lacking again was the explicit concept of quantized impedance in the maser.

While the 1970 paper by Landauer[50] somewhat clarified his earlier work, the explicit concept of impedance quantization remained obscure.

Quantization of mechanical impedance in the hydrogen atom was introduced in a 1975 unpublished note[51]. However, the quantity with units [kg/sec] was interpreted at that time to be related to mass flow in the deBroglie wave, with confusion arising again as a result of the inversion in the SI system of units. It was only recently that the correct impedance interpretation of that 1975 paper came to light[37].

Had exact impedance quantization been discovered in 1950 rather than 1980, one wonders whether the impedance concept might have found its way into the foundation of QED at that time, before it was set in the bedrock, to underpin rather than illuminate gravity and QFT [57–63].

MORE RECENT DEVELOPMENTS

More recent developments can be separated into two groups. In the first we see a gradually developing awareness of the importance of impedances in Atomic/Molecular/Optical and Condensed Matter physics. In the second we find the generalization of the impedance concept to all quantum potentials and forces.

Condensed Matter/AMO

Since the pivotal 1980 discovery of exact quantization, and particularly in the past few years, understanding of quantum impedances in electron dynamics, and particularly AMO and condensed matter, has been expanding at an accelerating rate, as shown by a sampling of the literature [64–109].

Extending the understanding beyond the photon and Landauer/quantum Hall impedances to the generalized impedances associated with all potentials appears to offer great promise in condensed matter physics[110]. The relevant length scale for the appropriate electron impedance network in condensed matter is not the Compton wavelength but rather the deBroglie wavelength, the wavelength of the Doppler-shifted Compton frequency[111].

Generalized Impedances

Once it was understood that the background independent mechanical impedances derived from Mach's principle[37, 51] could be defined for all forces, quantized by assigning a fundamental length, and converted to electromagnetic impedances by assigning a line charge density to the fundamental length, the progress was rapid.

- As shown in figure 2, aligning the impedance network with the coherence lengths of the unstable particles revealed a strong correlation between the two, suggesting that the impedance network might comprise a background independent model for the elementary particle spectrum[112].
- Calculating the impedance mismatch between the electron and the Planck particle revealed an exact relationship between gravity and electromagnetism[113].
- Applying the impedance concept to the measurement problem yielded explanations of state reduction, non-locality, and entanglement[114].
- A possible resolution of the black hole information paradox (presented at the 2013 Rochester Conference on Quantum Information and Measurement) followed from a synthesis of the previous three papers and the holographic principle[57].
- A presentation by Lev Vaidman at the Rochester conference[115, 116] motivated an impedance analysis of time symmetry in the nested Mach-Zender interferometer[117].
- Quantum Interpretations try to explain emergence of the world we observe from formal quantum theory. The impedance model was included in comparisons of selected interpretations[118].
- The chiral anomaly was analyzed via the impedance approach[42]
- A presentation file was prepared, summarizing and explaining the above results[55]

There has been substantial progress in the impedance approach in a surprisingly short amount of time, arguably sufficient to merit systematic and thorough critical examination of the logical foundations, results, and conclusions outlined here.

WHAT NEXT?

It would seem that the obvious next step is to put the impedance approach on a more formal theoretical foundation. The approach as it stands now evolved from the practical perspective of the pragmatic engineering physicist. While it is both logically coherent and computationally correct, having enjoyed substantial scrutiny within the physics community without meeting criticism other than what could be categorized as a matter of experience and convention rather than scientific fact, it could benefit from a more formal theoretical foundation.

On the practical side, if the approach proves useful then the greatest benefit will likely be in AMO/Condensed Matter. One possibility is design of superlattices[104, 110] matching the deBroglie impedance network of the electron. Another is impedance matching in the deuteron, with a cautious eye towards cold fusion. Both require adding dynamics to the model, namely the couplings and phases (the amplitudes are known, are what permit the calculations accomplished thus far) of the modes whose impedances comprise the network.

The requirement for dynamics is also present in particle physics, where the immediate goal is to map the standard model constituents onto the modes of the impedance network, the purpose being to understand proton and neutron spin structure[119–122] while RHIC (the world's only high energy collider with polarized beams) is still in operation, a potentially tenuous circumstance in the present economic climate.

And of course there is dark matter[123–125], whose presence dominates the impedance network and gives hope that the impedance approach will yield insight into the task of designing appropriate dark matter antennas and receivers.

SUMMARY

It appears that the impedance approach is far more radical than one might have imagined or desired. It deconstructs the Standard Model.

The weak force goes away. Anomalously long nuclear and unstable particle lifetimes can be understood as simple impedance mismatches, rather than as consequences of the postulated weak force. In the case of the unstable particles the impedance mismatch is to the photon, as can be see from figure 2. For coherence lengths greater than that of the neutral pion, none of the network impedances can be matched to the photon's scale invariant far field impedance. Instead, the much more difficult and improbable match to the neutrino's scale dependent impedance is required.

Mass generation via chiral symmetry breaking and the Higgs becomes irrelevant for two independent reasons. First, in the absence of the weak force there is no need for massive gauge bosons. And second, the chiral impedance is scale invariant, cannot communicate energy but rather only quantum phase, cannot deliver mass.

Similarly, mass generation in QCD via dynamic chiral symmetry breaking is seen to be not possible in light of the scale invariance of chiral impedances.

In the impedance approach the origin of mass is the energy in the fields of the coupled modes represented in the impedance network and confined by impedance mismatches. The calculated mass of the electron is correct at the nine significant digit limit of experimental accuracy, the muon at a part in one thousand, the pion at two parts in ten thousand, and the nucleon at seven parts in one hundred thousand[126].

The superheavies (top, Higgs, Z, W) appear to be incredibly short-lived excitations of the magnetic modes. Their coherence lengths sit at the 9.59 GeV electromagnetic fine structure line, in the middle of the dominant bottomonium decay modes.

CONCLUSION

The impedance approach to quantum field theory is truncating and tangential at best. The natural finiteness removes the need for regularization and renormalization, a major branch of QFT. Finiteness combined with the natural gauge invariance removes the anomalies, one of the most foundational aspects.

In keeping with the universal character of the impedance concept, the impedance approach has found direct and simple application to a variety of diverse topics at the core of the Standard Model and beyond, application to the unstable particle spectrum, the chiral anomaly, state reduction, non-locality, time asymmetry, gravitation, dark matter, electric dipole moments, and paradoxes in our systems of units.

Best of all, once the initial unfamiliarity passes the impedance approach is simple.

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