

# Chapter 1 *print vers 5/17/2018 Copyright of Robert D. Klauber*

## *Bird's Eye View*

*Well begun is half done.*

Old Proverb

### **1.0 Purpose of the Chapter**

Before starting on any journey, thoughtful people study a map of where they will be going. This allows them to maintain their bearings as they progress, and not get lost en route. This chapter is like such a map, a schematic overview of the terrain of quantum field theory (QFT) without the complication of details. You, the student, can get a feeling for the theory, and be somewhat at home with it, even before delving into the “nitty-gritty” mathematics. Hopefully, this will allow you to keep sight of the “big picture”, and minimize confusion, as you make your way, step-by-step, through this book.

### **1.1 This Book's Approach to QFT**

There are two main branches to (ways to do) quantum field theory called

- the canonical quantization approach, and
- the path integral (many paths, sum over histories, or functional quantization) approach.

The first of these is considered by many, and certainly by me, as the easiest way to be introduced to the subject, since it treats particles as objects that one can visualize as evolving along a particular path in spacetime, much as we commonly think of them doing. The path integral approach (which goes by several names), on the other hand, treats particles and fields as if they were simultaneously traveling all possible paths, a difficult concept with even more difficult mathematics behind it.

This book is primarily devoted to the canonical quantization approach, though I have provided a simplified, brief introduction to the path integral approach in Chap. 18 near the end. Students wishing to make a career in field theory will eventually need to become well versed in both.

### **1.2 Why Quantum Field Theory?**

The quantum mechanics (QM) courses students take prior to QFT generally treat a single particle such as an electron in a potential (e.g., square well, harmonic oscillator, etc.), and the particle retains its integrity (e.g., an electron remains an electron throughout the interaction.) There is no general way to treat transmutations of particles, such as that of a particle and its antiparticle annihilating one another to yield neutral particles such as photons (e.g.,  $e^- + e^+ \rightarrow 2\gamma$ ). Nor is there any way to describe the decay of an elementary particle such as a muon into other particles (e.g.  $\mu^- \rightarrow e^- + \nu + \bar{\nu}$ , where the latter two symbols represent neutrino and antineutrino, respectively).

Here is where QFT comes to the rescue. It provides a means whereby particles can be annihilated, created, and transmigrated from one type to another. In so doing, its utility surpasses that provided by ordinary QM.

There are other reasons why QFT supersedes ordinary QM. For one, it is a relativistic theory, and thus more all encompassing. Further, as we will discuss more fully later on, the straightforward extrapolation of non-relativistic quantum mechanics (NRQM) to relativistic quantum mechanics (RQM) results in states with negative energies, and in the early days of quantum theory, these were quite problematic. We will see in subsequent chapters how QFT resolved this issue quite nicely.

### **1.3 How Quantum Field Theory?**

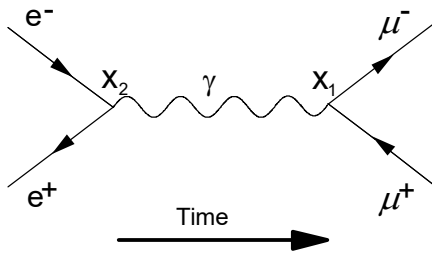
As an example of the type of problem QFT handles well, consider the interaction between an electron and a positron that produces a muon and anti-muon, i.e.,  $e^- + e^+ \rightarrow \mu^- + \mu^+$ , as shown in

*Limitation of original QM: no transmutation of particles*

*QFT: transmutation included*

*Energies <0  
RQM yes  
QFT no*

Fig. 1-1. At event  $x_2$ , the electron and positron annihilate one another to produce a photon. At event  $x_1$ , this photon is transmuted into a muon and an anti-muon. Antiparticles like positrons and anti-muons are represented by lines with arrows pointing opposite their direction of travel through time. The seemingly strange, reverse order of numbering here, i.e.,  $2 \rightarrow 1$ , is standard in QFT.



**Figure 1-1.  $e^- + e^+ \rightarrow \mu^- + \mu^+$  Scattering**

the sort shown pictorially via the Feynman diagram of Fig. 1-1. It turns out that the square of the absolute value of the transition amplitude equals the probability of finding (upon measurement) that the interaction occurred. This is similar to the square of the absolute value of the wave function in NRQM equaling the probability density of finding the particle.

QFT employs creation and destruction operators acting on states (i.e., kets), and these creation/destruction operators are part of the transition amplitude. We illustrate the general idea with the following grossly oversimplified transition amplitude, reflecting the interaction process of Fig. 1-1. Be cautioned that we have omitted, and even distorted a bit, some ultimately essential ingredients in the following, to make it simpler, and easier, to grasp the fundamental concept.

$$\text{Transition amplitude of Fig. 1-1} = \text{final} \langle \mu^+ \mu^- | \underbrace{K}_{\text{a constant from theory}} \left( \underbrace{\bar{\psi}_c^{\mu^-} A_d \psi_c^{\mu^+}}_{\text{virtual photon}} \right) \left( \underbrace{\bar{\psi}_d^{e^+} A_c \psi_d^{e^-}}_{\text{electron/positron annihilation}} \right) | e^+ e^- \rangle_{\text{initial}} \cdot \quad (1-1)$$

The ket  $|e^+e^- \rangle$  represents the incoming  $e^-$  and  $e^+$ ; the bra  $\langle \mu^+\mu^- |$ , the outgoing muon and anti-muon.  $K$  is a constant determined by theory.  $\psi_d^{e^-}$  is an operator that destroys the  $e^-$  in the ket;  $\bar{\psi}_d^{e^+}$ , an operator that destroys the  $e^+$ .  $\psi_c^{\mu^+}$  creates an anti-muon in the ket.  $\bar{\psi}_c^{\mu^-}$  creates a muon.  $A_c$  is an operator that creates a virtual photon, and  $A_d$  is an operator that destroys that virtual photon, with the lines underneath indicating that the photon is virtual and propagates (in Fig. 1-1 from  $x_2$  to  $x_1$ ). The mathematical procedure and symbolism (lines underneath) representing this virtual particle (photon here) process, as shown in (1-1), is called a contraction. When the virtual particle is represented as a mathematical function, it is known as the Feynman propagator or simply, the propagator, because it represents the propagation of a virtual particle from one event to another.

Note what happens to the ket part of the transition amplitude as we proceed, step-by-step, through the interaction process. First, the incoming particles (in the ket) are destroyed by the destruction operators, so at an intermediate point, we have

$$\text{Fig. 1-1 transition amplitude} = \text{final} \langle \mu^+ \mu^- | K \left( \bar{\psi}_c^{\mu^-} A_d \psi_c^{\mu^+} \right) \left( A_c \right) K_2 | 0 \rangle, \quad (1-2)$$

where the destruction operators have acted on the original ket to leave the vacuum ket  $|0 \rangle$  (no particles left) with a purely numeric factor  $K_2$  in front of it. The value of this factor is determined by the formal mathematics of QFT.

In the next step after (1-2), the virtual photon propagator, due to the creation operator  $A_c$ , creates a virtual photon (at  $x_2$  in Fig. 1-1) that then propagates (from  $x_2$  to  $x_1$  in the figure) and then, via  $A_d$ , is annihilated. This process leaves the vacuum ket still on the right along with an additional numeric factor, which comes out of the formal mathematics, and which we designate below as  $K_\gamma$ .

$$\text{Fig. 1-1 transition amplitude} = \text{final} \langle \mu^+ \mu^- | K \left( \bar{\psi}_c^{\mu^-} \psi_c^{\mu^+} \right) K_\gamma K_2 | 0 \rangle \quad (1-3)$$

*QFT example:  
 $e^- + e^+ \rightarrow \mu^- + \mu^+$   
scattering*

*Introductory overview with significant liberties taken from rigorous treatment in order to simplify as much as possible*

*Feynman propagator*

*Destruction operators leave vacuum ket times a numeric factor*

*Propagator action leaves only another numeric factor*

The remaining creation operators then create a muon and anti-muon out of the vacuum. This leaves us with the newly created ket  $|\mu^+ \mu^-\rangle$  times a numeric factor  $K_1$  in front. The ket and the bra now represent the same multi-particle state (same particles in the same states), so their inner product (the bracket) is not zero (as it would be if they were different states). Nor are there any operators left, but only numeric quantities, so we can move them outside the bracket without changing anything. Thus,

*Creation operators leave final state ket plus one more numeric factor*

$$\begin{aligned} \text{Fig. 1-1 transition amplitude} &= \text{final} \langle \mu^+ \mu^- | K K_1 K_\gamma K_2 | \mu^+ \mu^- \rangle_{\text{final}} \\ &= \text{final} \langle \mu^+ \mu^- | \underbrace{S_{\text{Fig1-1}}}_{\substack{\text{just a number} \\ \text{without operators}}} | \mu^+ \mu^- \rangle_{\text{final}} = S_{\text{Fig1-1}} \underbrace{\text{final} \langle \mu^+ \mu^- | \mu^+ \mu^- \rangle_{\text{final}}}_1 = S_{\text{Fig1-1}}, \end{aligned} \quad (1-4)$$

*Calculated amplitude*

where we note the important point that *in QFT the bracket of a multiparticle state* (inner product of multiparticle state with itself) such as that shown in (1-4) is defined so it *always equals unity*. Note, that if we had ended up with a ket different than the bra, the inner product would be zero, because the two (different) states, represented by the bra and ket, would be orthogonal. Examples are

*Bracket of multiparticle state = 1 in QFT*

$$\langle \mu^+ \mu^- | \underbrace{|\mu^- \mu^-\rangle}_{\text{two muons}} \rangle = 0, \quad \langle \mu^- \mu^+ | \underbrace{|e^+ e^-\rangle}_{\text{electron \& positron}} \rangle = 0, \quad \text{and} \quad \langle \mu^- \mu^+ | \underbrace{|\gamma\rangle}_{\text{single photon}} \rangle = 0. \quad (1-5)$$

Further, the inner product of any bra and ket with the same particle types but different states (e.g., different momentum for at least one particle in the bra from the ket) equals zero.

The whole process of Fig. 1-1 can be pictured as simply an evolution, or progression, of the original state, represented by the ket, to the final state, represented by the bra. At each step along the way, the operators act on the ket to change it into the next part of the progression. When we get to the point where the ket is the same as the bra, the full transition has been made, and the bracket then equals unity. What is left is our transition amplitude for the scattering of Fig. 1-1.

*Probability = |Amplitude|^2*

$$\text{Fig 1-1 probability of interaction} = S_{\text{Fig1-1}}^\dagger S_{\text{Fig1-1}} = |S_{\text{Fig1-1}}|^2. \quad (1-6)$$

The quantity  $KK_1K_\gamma K_2 = S_{\text{Fig1-1}}$  arising in (1-4) depends on particle momenta, spins, and masses, as well as the inherent strength of the electromagnetic interaction, all of which one would rightly expect to play a role in the probability of an interaction taking place. There are other subtleties, including some integration over  $x_1$  and  $x_2$ , that have been suppressed, and even distorted a bit, above in order to convey the essence of the transition amplitude as simply as possible.

From the interaction probability, scattering cross sections can be calculated.

### 1.4 From Whence Creation and Destruction Operators?

In NRQM, the solutions to the relevant wave equation, the Schrödinger equation, are states (particles or kets.) Surprisingly, the *solutions to the relevant wave equations in QFT are not states (not particles.)* In QFT, it turns out that these solutions are *actually operators that create and destroy states*. (The operators used in relations like (1-1) are actually just such solutions.) Different solutions exist that create or destroy every type of particle and antiparticle. In this unexpected (and, for students, often strange at first) twist lies the power of QFT.

*QFT wave equation solutions are operators*

### 1.5 Overview: The Structure of Physics and QFT's Place Therein

Students are often confused over the difference (and whether or not there is a difference) between relativistic quantum mechanics (RQM) and QFT. The following discussion, summarized below in Wholeness Chart 1-1, should help to distinguish them.

#### 1.5.1 Background: Poisson Brackets and Quantization

Classical particle theories contain rarely used entities called Poisson brackets, which, though it would be nice, are not necessary for you to completely understand at this point. (We will show their precise mathematical form in Chap. 2.) What you should realize now is that Poisson brackets are mathematical manipulations of certain pairs of properties (dynamical variables like position and momentum) that bear a striking resemblance to commutators in quantum theories. For example, the

*Poisson brackets behavior parallels quantum commutators*

Poisson bracket for position  $X$  (capital letters will designate Cartesian coordinates in this book) and momentum  $p_X$ , symbolically expressed herein as  $\{X, p_X\}$ , is non-zero (and equal to one), but the Poisson bracket for  $Y$  and  $p_X$  equals zero.

Shortly after NRQM theory had been worked out, theorists, led by Paul Dirac, realized that for each pair of quantum operators that had non-zero (zero) commutators, the corresponding pair of classical dynamical variables also had non-zero (zero) Poisson brackets. They had originally arrived at NRQM by taking classical dynamical variables as operators, and that led, in turn, to the non-zero commutation relations for certain operators (which result in other quantum phenomena such as uncertainty.) But it was soon recognized that one could do the reverse. One could, instead, take the classical Poisson brackets over into quantum commutation relations first, and because of that, the dynamical variables turn into operators. (Take my word for this now, but after reading the next section, do Prob. 6 at the end of this chapter, and you should understand it better.)

The process of extrapolating from classical theory to quantum theory became known as quantization. Apparently, for many, the specific process of starting with Poisson brackets and converting them to commutators was considered the more elegant way to quantize.

*Quantization:  
Poisson brackets  
become  
commutators*

### 1.5.2 First vs. Second Quantization

Classical mechanics has both a non-relativistic and a relativistic side, and each contains a theory of particles (localized entities, typically point-like objects) and a theory of fields (entities extended over space). All of these are represented in the first row of Wholeness Chart 1-1. Properties (dynamical variables) of entities in classical particle theories are *total* values, such as object mass, charge, energy, momentum, etc. Properties in classical field theories are *density* values, such as mass and charge density, or field amplitude at a point, etc. that generally vary from point to point. Poisson brackets in field theories are similar to those for particle theories, except they entail *densities* of the respective dynamical variables, instead of total values.

*Branches of  
classical  
mechanics*

With the success of quantization in NRQM, people soon thought of applying it to relativistic particle theory and found they could deduce RQM in the same way. Shortly thereafter they tried applying it to relativistic field theory, the result being QFT. The term first quantization came to be associated with *particle* theories (and is sometimes call particle quantization). The term second quantization became associated with *field* theories (and is sometimes called field quantization).

*1<sup>st</sup> quantization  
is for particles;  
2<sup>nd</sup> is for fields*

In quantizing, we also assume the classical Hamiltonian (total or density value) has the same quantum form. We can summarize all of this as follows.

#### First Quantization (Particle Theories)

- 1) Assume the quantum particle Hamiltonian has the same form as the classical particle Hamiltonian.
- 2) Replace the classical Poisson brackets for conjugate properties with commutator brackets (divided by  $i\hbar$ ), e.g.,

$$\{X_i, p_j\} = \delta_{ij} \Rightarrow [X_i, p_j] = X_i p_j - p_j X_i = i\hbar \delta_{ij} . \quad (1-7)$$

In doing (1-7), the classical properties (dynamical variables) of position and its conjugate 3-momentum become quantum non-commuting operators.

#### Second Quantization (Field Theories)

- 1) Assume the quantum field Hamiltonian density has the same form as the classical field Hamiltonian density.
- 2) Replace the classical Poisson brackets for conjugate property densities with commutator brackets (divided by  $i\hbar$ ), e.g.

$$\{\phi_r(\mathbf{x}, t), \pi_s(\mathbf{y}, t)\} = \delta_{rs} \delta(\mathbf{x} - \mathbf{y}) \Rightarrow [\phi_r(\mathbf{x}, t), \pi_s(\mathbf{y}, t)] = i\hbar \delta_{rs} \delta(\mathbf{x} - \mathbf{y}), \quad (1-8)$$

where  $\pi_s$  is the conjugate momentum density of the field  $\phi_s$ , different values for  $r$  and  $s$  mean different fields, and  $\mathbf{x}$  and  $\mathbf{y}$  represent different 3D position vectors. In doing (1-8), the classical field dynamical variables become quantum field non-commuting operators (and this, as we will see, has major ramifications for QFT.)

Note that the specific quantization we are talking about here (both first and second) is called canonical quantization, because, in both the Poisson brackets and the commutators, we are using (in classical mechanics terminology) canonical variables. For example,  $p_x$  is called the *canonical momentum* of  $X$ . (It is sometimes also called the *conjugate momentum*, as we did above, or the *generalized momentum* of  $X$ .)

*Our approach here: canonical quantization*

This differs from the form of quantization used in the path integral approach (see Sect. 1.1 on page 1) to QFT, which is known as functional quantization, because the path integral approach employs mathematical quantities known as *functionals* (See Chap. 18 near the end of the book for a brief introduction to this alternative method of doing QFT.)

*Path integral approach to QFT: functional quantization*

### 1.5.3 The Whole Physics Enchilada

All of the above two sections is summarized in Wholeness Chart 1-1. In using it, the reader should be aware that, depending on context, the term quantum mechanics (QM) can mean i) only non-relativistic (“ordinary”) quantum mechanics (NRQM), or ii) the entire realm of quantum theories including NRQM, RQM, and QFT. In the leftmost column of the chart, we employ the second of these.

Note that because quantum field applications usually involve photons or other relativistic particles, non-relativistic quantum field theory (NRQFT) is not widely applicable and thus rarely taught, at least not at elementary levels. However, in some areas where non-relativistic approximations can suffice, such as condensed matter physics, NRQFT can be useful because calculations are simpler. The term “quantum field theory” (QFT) as used in the physics community generally means “relativistic QFT”, and our study in this book is restricted to that.

**Wholeness Chart 1-1. The Overall Structure of Physics**

	<u>Non-relativistic</u>		<u>Relativistic</u>	
	<b>Particle</b>	<b>Field</b>	<b>Particle</b>	<b>Field</b>
<b>Classical mechanics (non-quantum)</b>	Newtonian particle theory	Newtonian field theory (continuum mechanics + gravity), e/m (quasi-static)	Relativistic macro particle theory	Relativistic macro field theory (continuum mechanics + e/m + gravity)
Properties (Dynamical variables) ⇓ Operators	⇓ 1 <sup>st</sup> quantization ⇓	⇓ 2 <sup>nd</sup> quantization ⇓	⇓ 1 <sup>st</sup> quantization ⇓	⇓ 2 <sup>nd</sup> quantization ⇓
<b>Quantum mechanics</b>	NRQM	NRQFT rarely taught.	RQM	QFT (not gravity)

As an aside, quantum theories of gravity, such as superstring theory and loop quantum gravity, are not included in the chart, as QFT in its standard model form cannot accommodate gravity. Thus, the relativity in QFT is special, but not general, relativity.

**Conclusions:** RQM is similar to NRQM in that both are particle theories. They differ in that RQM is relativistic. RQM and QFT are similar in that both are relativistic theories. They differ in that QFT is a field theory and RQM is a particle theory.

### 1.6 Comparison of Three Quantum Theories

NRQM employs the (non-relativistic) Schrödinger equation, whereas RQM and QFT must employ relativistic counterparts sometimes called relativistic Schrödinger equations. Students of QFT soon learn that each spin type (spin 0, spin 1/2, and spin 1) has a different relativistic Schrödinger equation. For a given spin type, that equation is the same in RQM and in QFT, and hence, both theories have the same form for the solutions to those equations.

*Different spin types → different wave equations*

The difference between RQM and QFT is in the meaning of those solutions. In RQM, the solutions are interpreted as states (particles, such as an electron), just as in NRQM. In QFT, though it may be initially disorienting to students previously acclimated to NRQM, the solutions turn out not to be states, but rather operators that create and destroy states. Thus, QFT can handle transmutation of particles from one kind into another (e.g., muons into electrons, by destroying the original muon and creating the final electron), whereas NRQM and RQM cannot. Additionally, the problem of negative energy state solutions in RQM does not appear in QFT, because, as we will see, the creation and destruction operator solutions in QFT create and destroy both particles and anti-particles. Both of these have positive energies.

Additionally, while RQM (and NRQM) are amenable primarily to single particle states (with some exceptions), QFT better, and more easily, accommodates multi-particle states.

In spite of the above, there are some contexts in which RQM and QFT may be considered more or less the same theory, in the sense that QFT encompasses RQM. By way of analogy, classical relativistic particle theory is inherent within classical relativistic field theory. For example, one could consider an extended continuum of matter which is very small spatially, integrate the mass density to get total mass, the force/unit volume to get total force, etc., resulting in an analysis of *particle* dynamics. The field theory contains within it, the particle theory.

In a somewhat similar way, QFT deals with relativistic states (kets), which are essentially the same states dealt with in RQM. QFT, however, is a more extensive theory and can be considered to encompass RQM within its structure.

And in both RQM and QFT (as well as NRQM), operators act on states in similar fashion. For example, the expected energy measurement is determined the same way in both theories, i.e.,

$$\bar{E} = \langle \phi | H | \phi \rangle, \quad (1-9)$$

with similar relations for other observables.

These similarities and differences, as well as others, are summarized in Wholeness Chart 1-2. The chart is fairly self explanatory, though we augment it with a few comments. You may wish to follow along with the chart as you read them (below).

The different relativistic Schrödinger equations for each spin type are named after their founders (see names in chart.) We will cover each in depth. At this point, you have to simply accept that in QFT their solutions are operators that create and destroy states (particles). We will soon see how this results from the commutation relation assumption of 2<sup>nd</sup> quantization (1-8).

With regard to phenomena, I recall wondering, as a student, why some of the fundamental things I studied in NRQM seemed to disappear in QFT. One of these was bound state phenomena, such as the hydrogen atom. None of the introductory QFT texts I looked at even mentioned, let alone treated, it. It turns out that QFT can, indeed, handle bound states, but elementary courses typically don't go there. Neither will we, as time is precious, and other areas of study will turn out to be more fruitful. Those other areas comprise scattering (including inelastic scattering where particles transmute types), deducing particular experimental results, and vacuum energy.

I also once wondered why spherical solutions to the wave equations are not studied, as they play a big role in NRQM, in both scattering and bound state calculations. It turns out that scattering calculations in QFT can be obtained to high accuracy with the simpler plane wave solutions. So, for most applications in QFT, they suffice.

Wave packets, as well, can seem nowhere to be found in QFT. Like the other things mentioned, they too can be incorporated into the theory, but simple sinusoids (of complex numbers) serve us well in almost all applications. So, wave packets, too, are generally ignored in introductory (and most advanced) courses.

Wave function collapse, a much discussed topic in NRQM, is generally not a topic of focus in QFT texts. It does, however, play a key, commonly hidden role, which is discussed herein in Sects. 7.4.3 and 7.4.4, pgs. 196-197.

The next group of blocks in the chart points out the scope of each theory with regard to the four fundamental forces. Nothing there should be too surprising.

The final blocks note the similarities and differences between forces (interactions) in the different theories. As in classical theory, in all three quantum theories, interactions comprise forces that change the momentum and energy of particles. However, in QFT alone, interactions can also

*Solutions:  
RQM → states  
QFT → operators*

*QFT can be done  
without negative  
energies*

*QFT:  
multiparticle*

*RQM  
contained in  
QFT*

*Calculate  
expectation  
values in  
same way*

*Phenomena in  
the 3 theories*

*QFT rarely  
uses spherical  
solutions*

*or wave  
packets*

*QFT handles  
various type  
interactions*

involve changes in type of particle, such as shown in Fig. 1-1. At event  $x_2$ , the electron and positron are changed into a photon, and in the process energy and momentum is transferred to the photon.

**Wholeness Chart 1-2. Comparison of Three Theories**

	<u>NRQM</u>	<u>RQM</u>	<u>QFT</u>
<b>Wave equation</b>	Schrödinger	Klein-Gordon (spin 0) Dirac (spin $\frac{1}{2}$ ) Proca (spin 1) Special case of Proca: $\checkmark$ Maxwell (spin 1 massless)	Same as RQM at left
<b>Solutions to wave equation</b>	States	States	Operators that create and destroy states
<b>Negative energy?</b>	No	Yes	No
<b>Particles per state</b>	Single*	Single*	Multi-particle
<b>Expectation values</b>	$\bar{O} = \langle \phi   O   \phi \rangle$	As at left, but relativistic.	As at left in RQM.
<b>Phenomena:</b>			
1. bound states	Yes, non-relativistic	Yes, relativistic	Yes (usually not studied in introductory courses)
2. scattering			
a. elastic	a. Yes	a. Yes	a. Yes
b. inelastic (transmutation)	b. No (though some models can estimate)	b. Yes and no. (i.e., cumbersome and only for particle/antiparticle creation & destruction.)	b. Yes
3. decay			
a. composite particles	a. Yes (tunneling)	a. Yes	a. Yes
b. elementary particles	b. No	b. No	b. Yes
4. vacuum energy	No	No	Yes
<b>Coordinates</b>			
1. Cartesian (plane waves)	Free, 1D potentials, particles in “boxes”	As at left	Used primarily for free particles, particles in “boxes”, and scattering.
2. Spherical (spherical waves)	Bound states and scattering.	As at left.	Not usually used in elementary courses.
<b>Wave Packets</b>	Yes	Yes	Yes, but rarely used. Not taught in intro courses.
<b>Wave function collapse</b>	Yes	Yes	Yes, but not usually noted and behind the scenes. (See Sects. 7.4.3 & 4)

<b>Interaction types</b>			
1. e/m	No, though can pseudo model	As at left	Yes
2. weak	No	No	Yes
3. strong	No*	No*	Yes
4. gravity	No	No	Not as of this edition date.
<b>Interaction nature</b>			
Transfers energy & momentum?	Yes	Yes	Yes
Can change particle type?	No	No	Yes

\*Some caveats exist for this chart. For example, NRQM and RQM can handle certain multiparticle states (e.g. hydrogen atom), but QFT generally does it more easily and more extensively. And the strong force can be modeled in NRQM and RQM by assuming a Yukawa potential, though a truly meaningful handling of the interaction can only be achieved via QFT.

### 1.7 Major Components of QFT

There are four major components of QFT, and this book (after the first two foundational chapters) is divided into four major parts corresponding to them. These are:

*The four major parts of QFT*

#### 1. Free (non-interacting) fields/particles

The field equations (relativistic Schrödinger equations) have no interaction terms in them, i.e., no forces are involved. The solutions to the equations are free field solutions.

#### 2. Interacting fields/particles

In principle, one would simply add the interaction terms to the free field equations and find the solutions. As it turns out, however, doing this is intractable, at best (impossible, at least in closed form, is a more accurate word). A trick employed in interaction theory actually lets us use the free field solutions of 1 above, so those solutions end up being quite essential throughout all of QFT.

#### 3. Renormalization

If you are reading this text, you have almost certainly already heard of the problem with infinities popping up in the early, naïve QFT calculations. The calculations referred to here are specifically those of the transition amplitude (1-4), where some of the numeric factors, if calculated straightforwardly, turn out to be infinite. Renormalization is the mathematical means by which these infinities are tamed, and made finite.

#### 4. Application to experiment

The theory of parts 1, 2, and 3 above are put to practical use in determining interaction probabilities and from them, scattering cross sections, decay probabilities (half-lives, etc.), and certain other experimental results. Particle decay is governed by the weak force, so we will not do anything with that in the present volume, which is devoted solely to quantum electrodynamics (QED), involving only the electromagnetic force.

### 1.8 Points to Keep in Mind

When the word “field” is used classically, it refers to an entity, like fluid wave amplitude, **E**, or **B**, that is spread out in space, i.e., has different values at different places. By that definition, the wave function of ordinary QM, or even the particle state in QFT, is a field. But, it is important to realize that in quantum terminology, the word “field” means an operator field, which creates and destroys particle states. States (= particles = wave functions = kets) are *not* considered fields in that context.

*Terminology  
“field”=  
operator in  
QFT*



In this text, the symbol  $e$ , representing the magnitude of charge on an electron or positron, is always positive. The charge on an electron is  $-e$ .

*Symbol  $e > 0$*

### 1.9 Big Picture of Our Goal

The big picture of our goal is this. We want to understand Nature. To do so, we need to be able to predict the outcomes of particle accelerator scattering experiments, certain other experimental results, and elementary particle half-lives. To do these things, we need to be able to calculate probabilities for each to occur. To do that, we need to be able to calculate transition amplitudes for specific elementary particle interactions. And for that, we need first to master a fair amount of theory, based on the postulates of quantization.

*Our goal: predict scattering and decay seen in Nature*

We will work through the above steps in reverse. Thus, our immediate goal is to learn some theory in Parts 1 and 2. Then, how to formulate transition amplitudes, also in Part 2. Necessary refinements will take up Part 3, with experimental application in Part 4.

#### Steps to our goal

2<sup>nd</sup> quantization postulates  $\rightarrow$  QFT theory  $\rightarrow$  transition amplitude calculation  $\rightarrow$  probability  
 $\rightarrow$  scattering, decay, other experimental results  $\rightarrow$  confirmation of QFT

*Steps to our goal*

In this book our goal is a bit limited, as we will examine a part – an essential part – of the big picture. We will i) develop the fundamental principles of QFT, ii) use those principles to derive quantum electrodynamics (QED), the theory of electromagnetic quantum interactions, and iii) apply the theory of QED to electromagnetic scattering and other experiments. We will not examine herein the more advanced theories of weak and strong interactions, which play essential roles in particle decay, most present day high energy particle accelerator experiments, and composite particle (e.g., proton) structure. Weak and strong interaction theories build upon the foundation laid by QED. First things first.

*Our goal in this book: basic QFT principles and QED, theory and experiments*

### 1.10 Summary of the Chapter

Throughout this book, we will close each chapter with a summary, emphasizing its most salient aspects. However, the present chapter is actually a summary (in advance) of the entire book and all of QFT. So, you, the reader, can simply look back in this chapter to find appropriate summaries. These should include Sect. 1.1 (This Book's Approach to QFT), the transition amplitude relations of Eqs. (1-1) through (1-6), Sect.1.5.2 (1<sup>st</sup> and 2<sup>nd</sup> Quantization), Wholeness Chart 1-1 (The Overall Structure of Physics), Wholeness Chart 1-2 (Comparison of Three Theories), and Sect. 1.9 (Big Picture of Our Goal).

### 1.11 Suggestions?

If you have suggestions to make the material anywhere in this book easier to learn, or if you find any errors, please let me know via the web site address for this book posted on pg. xvi (opposite pg.1). Thank you.

### 1.12 Problems

As there is not much in the way of mathematics in this chapter, for most of it, actual problems are not really feasible. However, you may wish to try answering the questions in 1 to 5 below without looking back in the chapter. Doing Prob. 6 can help a lot in understanding first quantization.

1. Draw a Feynman diagram for a muon and anti-muon annihilating one another to produce a virtual photon, which then produces an electron and a positron. Using simplified symbols to represent more complex mathematical quantities (that we haven't studied yet), show how the transition amplitude of this interaction would be calculated.
2. Detail the basic aspects of first quantization. Detail the basic aspects of second quantization, then compare and contrast it to first quantization. In second quantization, what is analogous to position in first quantization? What is analogous to particle 3-momentum?

3. Construct a chart showing how non-relativistic theories, relativistic theories, particles, fields, classical theory, and quantum theory are interrelated.
4. For NRQM, RQM, and QFT, construct a chart showing i) which have states as solutions to their wave equations, ii) how to calculate expectation values in each, iii) which can handle bound states, inelastic scattering, elementary particle decay, and vacuum fluctuations, iv) which can treat the following interactions: i) e/m, ii) weak, iii) strong, and iv) gravity.
5. What are the four major areas of study making up QFT?
6. Using the corresponding Poisson bracket relation  $\{X, p_x\} = 1$ , we deduce, from first quantization postulate #2, that, quantum mechanically,  $[X, p_x] = i\hbar$ . For this commutator acting on a function  $\psi$ , i.e.,  $[X, p_x] \psi = i\hbar \psi$ , determine, assuming  $p_x$  is a single term, what form  $p_x$  must have. Is this an operator? Does it look like what you started with in elementary QM, and from which you then derived the commutator relation above? Can we go either way?

Then, take the eigenvalue problem  $H\psi = E\psi$ , and use the same form of the Hamiltonian  $H$  as used in classical mechanics (i.e.,  $p^2/2m + V$ ), with the operator form you found for  $p$  above. This last step is the other part of first quantization (see page 4).

Did you get the time independent Schrödinger equation? (You should have.) Do you see how, by starting with the Poisson brackets and first quantization, you can derive the basic assumptions of NRQM, i.e., that dynamical variables become operators, the form of those operators, and even the time independent Schrödinger equation, itself? We won't do it here, but from that point, one could deduce the time dependent Schrödinger equation, as well.