Quanta and Particles in Quantum Field Theory

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Vienna, June 3rd 2026

Field-Particle Duality

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- Nonrelativistic QM, with or without interactions, can likewise be reformulated as a field theory and the duality is likewise exact

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- Particles and fields don't match 1:1 in the Standard Model (Bain)
- The duality relies on a decoupling of fields into uncoupled oscillators that just doesn't hold

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- Occasionally you hear that particles don't exist
- Mostly, philosophers say that particles are *emergent*
- But what — at the level of formal structure — are these emergent entities?

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- Requires UV cutoff to be well-defined and IR cutoff to circumvent Haag's theorem, but that's okay

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  - No particle associated with the quark field
  - No field (in the Hamiltonian) associated with the proton, pion, etc.

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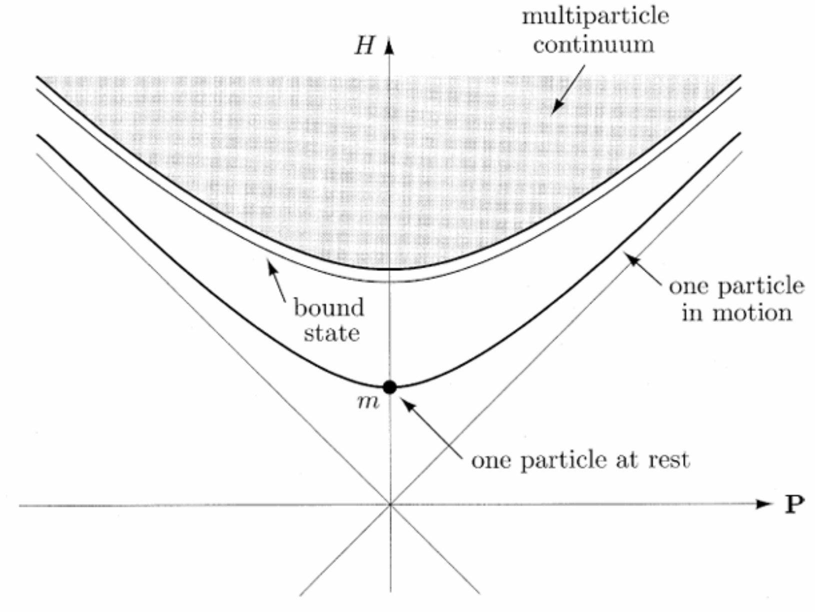
- (Boltzmann regime in statistical mechanics and kinetic theory)

(Peskin and Schroeder p.213)



Single-particle states

If f is a function on spacetime approximately localized at event x and with Fourier transform overlapping with a particle mass shell but no other occupied region, then (up to normalization)

$$\widehat{a}_f^\dagger |\Omega\rangle = \int \mathrm{d}x^4\, f(x)\widehat{\phi}(x)\,|\Omega\rangle$$

is a 1-particle state (of that particle),

$$\widehat{a}_f^\dagger |\Omega\rangle \propto \int \frac{\mathrm{d}k^3}{(2\pi)^3 2\omega_k} \tilde{f}(\mathbf{k}, \omega_k)\,|\mathbf{k}\rangle$$

Multiparticle states

If $f_1, \ldots f_n$ are N such functions localized at events $x_1, \ldots x_n$ all at some (finite!) time t_i and separated by $\gg 1/m$, then (via the Cluster Decomposition Theorem) up to exponentially small corrections,

$$|f_1, \cdots f_n\rangle \equiv \widehat{a}^\dagger_{f_n} \cdots \widehat{a}^\dagger_{f_1} |\Omega\rangle$$

will behave as an n-particle state as long as the wavepackets remain non-overlapping

Scattering (I)

If we similarly construct a state $|g_1, \ldots g_m\rangle$ describing an m-particle state at a later time, then

$$\langle g_1, \ldots g_m | f_1, \ldots f_n \rangle$$

is the scattering amplitude between the two states and can be expressed in terms of the $n + m$-point function,

$$\langle g_1, \ldots g_m | f_1, \ldots f_n \rangle \propto$$

$$\int \mathrm{d}x^{4m} \, \mathrm{d}y^{4n} \, \mathcal{G}(x_1, \cdots x_m, y_1, \cdots y_n) g_1(x_1) \cdots g_m(x_m) f_1(y_1) \cdots f_n(y_n)$$

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- Spatially narrower wavepackets can resolve scale effects in interactions, e.g. long-lived resonances, long(er)-range forces

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- Method: *effective field theory*. Write down the most general nonrelativistic theory of electrons and photons and evaluate the coefficients by matching to QED cross-sections.
- (Resultant theory is non-unitary in some circumstances, e.g. electron/positron annihilation)

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- "Particles are emergent" is the beginning rather than the end of the conversation
- The quanta of perturbed harmonic oscillators provide a useful but very thin notion of particle — to thin to do all the work that 'particle' does in physics
- Much more robust notions are available through scattering theory and nonrelativistic EFT
- These notions are approximate and domain-dependent, but non-perturbative