What is a particle?

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Happy birthday Abhay !!

It is a very exciting time for Loop Quantum Gravity

- Applications
  - Loop Quantum Cosmology
  - Quantum black holes
- Theory
  - Barret-Crane vertex corrected: novel vertex amplitude
  - Correct recovery of the classical limit
  - Covariant (spinfoam) and canonical (spin networks) finally united
  - Scattering amplitudes of gravitons are beginning to be computed

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gravitons ????

But there are no “particles” in quantum gravity !

A strange disagreement

From particle physics:

1. Weinberg's definition and construction of QFT is based on the notion of particle.

2. *Quantum Mechanics + Special Relativity = particles*: The Hilbert space $\mathcal{H}$ carries a representation of the Poincaré group; its irreducible components, labelled by mass and spin (Wigner), are one-particle states. (*Are they?*)

3. Particles are the *quanta of the (free) field*: the modes $\phi(k)$ are oscillators: their energy is quantized. A particle is a quantum superposition of one-quantum excitations of these modes: $|\,f\,\rangle = \int dk\ f(k)\,|\,k\,\rangle$, where $|\,k\,\rangle = \phi(k)\,|\,0\,\rangle$ is the first excitation of the mode k.

4. Further complications: interacting theories, QCD... Other definitions of particles (poles in the green function...)

5. *Detectors* (CERN detectors, photoelectric cells, scintillators...) detect particles.

Unquestionable conclusion: matter is made out of *particles*.

From the general relativity community:

1. In the real world, spacetime is curved → Wigner argument does not apply.
2. Unruh effect → already in flat space, a (accelerated) detector "detects particles" even with the field in the vacuum.
3. The mode decomposition depends on the (arbitrary) choice of a foliation → the notion of "particle" as excitations of modes is physically meaningless.
4. Bob Wald: QFT must be interpreted in terms of *local observables* (ex: the integral of energy-momentum-tensor components over a finite region), not in terms of particles.
5. Paul Davies: *" Particles do not exist! "*

Unquestionable conclusion:
particles are not the appropriate way to describe quantum matter.

Who is right?

If the relativists are right, how come particle detectors detect particles (even if real spacetime is curved)? What is the object detected by a particle detector in curved spacetime? Whatever it is, isn't it still a particle? How to describe it theoretically?

If the particle physicists are right, what are the true particle states in a curved spacetime? What are the true particle states in quantum gravity?

A strictly related problem:

A particle is a local or a global object?

1. Particle states in Fock space are global objects: *they aren't eigenstates of any local operators.*

2. But particle detectors have *finite* size, and see particles as local objects.

3. Example: the Fock vacuum is the state with no particles, but any finite size detector do detects particles in the Fock vacuum.

Solution:

There exist two different kinds of states in QFT:

global (particle) states and local (particle) states.

They are almost the same, but not precisely the same.
Distinguishing the two brings clarity to the above questions.

More precisely:

1. In flat space QFT:
   – global states are in the standard Fock space basis (eigenstates of the particle number operator).
   – local states are the eigenstates of the operators representing measurements by finite-size detectors.

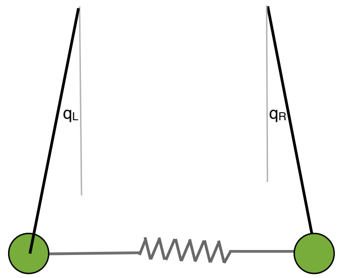
2. Global states converge weakly (but not in norm!) to local states, when detectors are large.

3. Global states (used in QFT textbooks) are very good approximations to the true states detected in the real world, which are the local states.

4. In curved spacetime, global states do not exist anymore. But, local states still exist. They are eigenstates of local operators with discrete spectrum (such as the energy of a region), describing localized measurements. They have virtually the same properties as the textbook QFT particle states, for large detectors.

In other words: everybody is right, but both points of view miss something.

First step: two oscillators



$$
\begin{aligned}
H &= H_L + H_R + V \\
&= \frac{p_L^2 + \omega^2 \, q_L^2}{2} + \frac{p_R^2 + \omega^2 \, q_R^2}{2} + \lambda \, q_L q_R,
\end{aligned}
$$

A basis in $\mathcal{H}$:

$$H_{L,R}|n_L, n_R\rangle_{\rm loc} \; = \; \hbar\omega(n_{L,R} + \frac{1}{2}) \; |n_L, n_R\rangle_{\rm loc}.$$

In particular:

$$|0\rangle_{\rm loc} \; \equiv \; |0,0\rangle_{\rm loc}$$

is a state with no quanta on L and no quanta on R. And

$$|L\rangle_{\rm loc} \; \equiv \; |1,0\rangle_{\rm loc}$$

is a state with “one quantum on the L oscillator”.

Normal modes: $q_a = \frac{q_L + q_R}{\sqrt{2}}, \quad q_b = \frac{q_L - q_R}{\sqrt{2}}.$

with: $H = H_a + H_b = \frac{p_a^2 + \omega_a^2\ q_a^2}{2} \ + \ \frac{p_b^2 + \omega_b^2\ q_b^2}{2}.$

Another basis in $\mathcal{H}$:

$$H_{a,b}|n_a, n_b\rangle_{\rm glob} \ = \ \hbar\omega_{a,b}(n_{a,b} + \frac{1}{2})\ |n_a, n_b\rangle_{\rm glob}$$

In particular:

$$|0\rangle_{\rm glob} \ \equiv \ |0,0\rangle_{\rm glob}$$

is a state with no quanta either mode. A generic "one particle state" in this basis

$$|\psi\rangle_{\rm glob} \ = \alpha\ |1,0\rangle_{\rm glob} + \beta\ |0,1\rangle_{\rm glob}$$

In particular

$$|L\rangle_{\rm glob} \ := \frac{|1,0\rangle_{\rm glob} + \ |0,1\rangle_{\rm glob}}{\sqrt{2}}$$

is a quantum oscillation maximally concentrated on the L oscillator.

What is the relation between $|L\rangle_{\rm loc}$ and $|L\rangle_{\rm glob}$? They are both states where the Left oscillator is excited, but they are different:

$$\langle q_L, q_R|L\rangle_{\rm loc} = \sqrt{\frac{2\omega^3}{\pi}}\; q_L\; e^{-\frac{\omega}{2}(q_L^2+q_R^2)}$$

while

$$\langle q_L, q_R|L\rangle_{\rm glob} =$$
$$\frac{\sqrt[4]{\omega_a\omega_b}}{\sqrt{2\pi}}\left(\frac{\sqrt{\omega_a}+\sqrt{\omega_b}}{2}\,q_L+\frac{\sqrt{\omega_a}-\sqrt{\omega_b}}{2}\,q_R\right)\, e^{-\frac{\omega_a+\omega_b}{4}(q_L^2+q_R^2)+\frac{\omega_a-\omega_b}{4}q_L q_R}$$

But not very different: If λ is small, $\omega_a \sim \omega_b \sim \omega$ and the two states are very similar. In fact:

$$_{\rm loc}\langle L|L\rangle_{\rm glob} \quad = \quad 1 - O(\lambda^2).$$

Also

$$|L\rangle_{\rm glob} \; = \; |L\rangle_{\rm loc} \; - \; \frac{\lambda}{\sqrt{8}\,\omega^2}\;|2,1\rangle_{\rm loc} + O(\lambda^2).$$

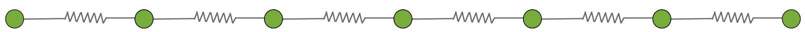
The two states $|L\rangle_{\rm glob}$ and $|L\rangle_{\rm loc}$ are both "one-particle states" in which the "particle" is concentrated on the oscillator q_L, but they are distinct states.

$|L\rangle_{\rm glob}$: quantum excitation of global oscillation modes. Not an eigenstate of local operators. The q_L variable is excited, but it is also correlated with the q_R variable.

$|L\rangle_{\rm loc}$: quantum excitation of a local variable. Eigenstate of local operators. The q_L variable is excited, and it is not correlated with the q_R variable.

Notice: if I measure if the q_L variable is excited and find out it is (say I measure H_L and obtain the first excited energy level), I project the state on $|L\rangle_{\rm loc}$.

Second step: chain of oscillators



$$H = \sum_{i=1}^{n} \frac{1}{2} \left(p_i^2 + q_i^2 \right) + \lambda \sum_{i=1}^{n-1} q^i q^{i+1}$$

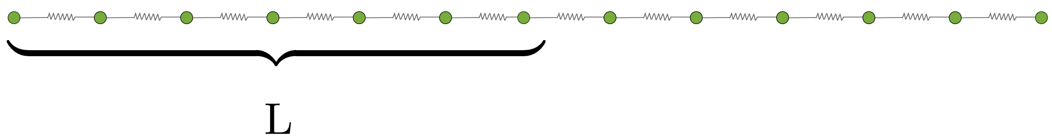
Normal modes $\mathbf{Q} = (Q_a), a = 1, \ldots, n$ are given by $\mathbf{Q} = U^{(n)}\mathbf{q}$, where $U^{(n)}_{ai} = \sqrt{\frac{2}{n+1}} \sin\left(\frac{ai\pi}{n+1}\right)$. A basis that diagonalizes H is given by the states $|\mathbf{n}\rangle = |n_1, \ldots n_n\rangle$ with n_a quanta in the a-th normal mode. The number operator is

$$N \; |\mathbf{n}\rangle = \left(\sum_{a=1}^{n} \; n_a \right) \; |\mathbf{n}\rangle.$$

one-particle states: $|a\rangle = |0, \ldots, 1, \ldots, 0\rangle$. The state

$$|i\rangle_{\text{glob}} = \sum_{a=1}^{n} \; (U^{(n)})^{-1}_{ia} \; |a\rangle$$

is the one-particle state maximally concentrated on the i-th oscillator.



Local states

$$H = H_L + H_R + V$$

Choose a basis that diagonalizes H_L and H_R. For this we need the eigenmodes of H_L alone. $|n_1^L, ..., n_{n_L}^L; n_1^R, ..., n_{n_R}^R\rangle$. Let $|a\rangle_{\rm loc} = |0, ..., 1, ...0; 0, ..., 0\rangle$ be the excitations of the a'th left eigenmode. Then the state

$$|i\rangle_{\rm loc} \quad = \quad \sum_{a=1}^{n_1} (U^{(n_L)})^{-1}_{ia} |a\rangle_{\rm loc}$$

is the local one-particle state, associated to the region L, with the particle on the i-th oscillator.

$|i\rangle_{\text{glob}}$: quantum excitation of global oscillation modes. Not an eigenstate of any local operator. The q_i variable is excited, and it is also (weakly) correlated with *all* q_i variables.

$|i\rangle_{\text{loc}}$: quantum excitation of a the modes of the L region. The q_i variable is excited, and it is correlated only with the variables in L. It is an eigenstate of observables in the region L.

If I make a measurement with an apparatus having only access to variables in L, I can project the state on $|i\rangle_{\text{loc}}$, but not on $|i\rangle_{\text{glob}}$.

Is it still true that $|i\rangle_{\rm glob}$ and $|i\rangle_{\rm loc}$ are "very similar"? Yes, but:

⇒ Surprisingly, we still have

$${}_{\rm glob}\langle i|i\rangle_{\rm loc} \sim 1 - \frac{\lambda^2}{16}$$

for any n and n_L: the scalar product does *not* go to 1 when the regions become large.

⇒ However, the *expectation value* of *local* operators is the same for $|i\rangle_{\rm glob}$ and $|i\rangle_{\rm loc}$ when the regions become large. For instance

$${}_{\rm glob}\langle i|q_i q_j|i\rangle_{\rm glob} - {}_{\rm loc}\langle i|q_i q_j|i\rangle_{\rm loc} \longrightarrow 0$$

at every order in λ when $n, n_L \to \infty$.

Third step: field theory

Scalar massive field theory in 1+1 dimension. Fix a finite region L.

Define the (usual) global one-particle states $|f\rangle_{\rm glob}$, where $f(x)$ is a compact-support function, by

$$|f\rangle_{\rm glob} = \int dk\ \tilde{f}(k)|k\rangle,$$

where k are the eigenmodes of the field.

Define the local one-particle states $|f\rangle_{\rm loc}$, where $f(x)$ is a compact-support function, by

$$|f\rangle_{\rm loc} = \int dk\ \tilde{f}(k)|k\rangle,$$

where k are the eigenmodes of the L region.

Then again, local and global states converge weakly with the size of the region: the *expectation value* of *local* operators is the same for $|f\rangle_{\rm glob}$ and $|f\rangle_{\rm loc}$ when: the size of the regions is large with respect to the Compton wavelength and the support of f is away from the boundary (exponential convergence). In particular

$${}_{\rm glob}\langle 0|\phi(x,t)\phi(x',t')|0\rangle_{\rm glob} - {}_{\rm loc}\langle 0|\phi(x,t)\phi(x',t')|0\rangle_{\rm loc} \to 0$$

Interpretation

Particles detected by real measuring apparatus are local objects. They are best represented by QFT states that are eigenstates of local operators. I have defined these states, and denoted them *local particle states*.

This is not what is usually done in QFT, where, instead, we represent the particles observed in particle detectors by means of a different set of states: *global particle states* such as the n-particle Fock states.

Global particle states provide a **good approximation** to local particle states. The convergence is not in the Hilbert space norm, but in a weak topology given by local observables.

Answers to the questions posed

– **Local or global?: Local.**

The global properties of the particle states are an artifact of an *approximation* taken, not an intrinsic property of physically observed particles.

– **Can the notion of particle be utilized in a curved context? Yes.**

Particles can be understood as eigenstates of local operators, with no reference to global features.

On a curved spacetime, a detector that measures the energy H_L in a finite region of space L, can detects local particle states which are eigenstates of H_L. These states have a particle-like structure.

$\rightarrow$ *global* particle states do not generalize, but *local* particle states, that truly describe what we measure in a bubble chamber, do.

– **Can we view QFT, in general, as a theory of particles? Yes, but.**

Global particle states are defined once and for all in the theory; while each finite size detector defines its own bunch of local particle states.

The world is far more subtle than a bunch of particles that interact

Will Abhay agree?

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Thanks for everything, Abhay !