Minimum uncertainty states for a free particle with quantized mass-energy

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Abstract..
Composite particles – e.g. atoms, molecules – are promising tools for testing joint quantum and general relativistic phenomena or macroscopic limits of quantum mechanics. However, in all theoretical studies of such particles, freely propagating, they delocalise into separate internal mass-energy components, destroying spatial coherence, and rendering them unsuitable for experimental applications. We here provide a solution to this problem[1]. By formulating a new uncertainty inequality for position and velocity, we derive its minimising states, and prove they fully overcome this delocalisation effect.
While addressing an open theory question, and a pressing issue for next-generation experiments, our results initiate a systematic exploration of new configuration-space uncertainty principles, also with further experimental applications.

Keywords: quantum foundations, decoherence, atom optics, quantum & gravity

As experimental quantum technologies increase in complexity and precision, the loss of spatial coherence is a problem which will only grow larger. Nonetheless, the same complexity and precision is bringing us closer to tests of fundamental physics, particularly quantum effects due to time dilation of the internal degrees of freedom of composite particles [2].
Theoretical studies of such particles under free propagation [3,4] found they delocalise into separate internal energy components, each travelling at different speeds (see Figure 1). If this is unavoidable behaviour, it will be both detrimental for all future experiments and metrology schemes with composite quantum systems, and cast doubt on the suitability of particles like atoms as idealised models of clocks in quantum physics. Thus it is currently an open question:
What is the optimal way to prepare composite particles to avoid the delocalisation problem, and the related loss of spatial coherence?
We here provide an answer to this question.

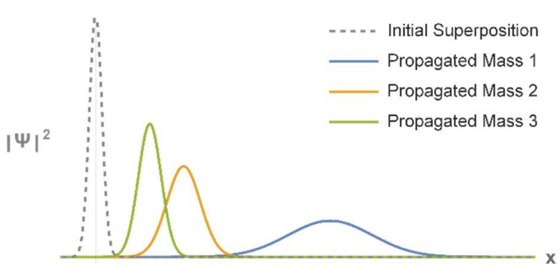

Figure 1 A propagating particle in a generic Gaussian superposition state delocalises.

Considering that mass-energy equivalence requires that internal energy contributes to a particle's mass, even at low energies, the phase- and configuration- (position and velocity) space for composite particles are not trivially related. We construct an uncertainty inequality for position and velocity (rather than momentum) and find the states that minimise it.
Upon propagation, the mass-energy components of our new minimum uncertainty state all move on the same space-time trajectory, and thus do not delocalise (see Figure 2).

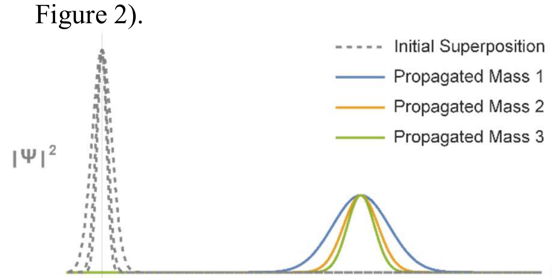

Figure 2 A propagating particle prepared in our x-v minimising uncertainty state does not delocalise.

Furthermore, the MUS is more localised than a generic phase-space-minimising Gaussian even when there is no propagation, with $\Delta x^2_{MUS}(t) \leq \Delta x^2_{Gaussian}(t)$.
These new minimum uncertainty states will find applications in various precision experimental tests, while the result also highlights the fundamental differences between phase and configuration space for composite particles, and further exploration of configuration space uncertainty principles may help address other fundamental issues where internal and external degrees of freedom are coupled.

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