



Contribution ID: 109

Type: Poster

Foundations of Quantum Tunnelling in Interacting Systems

Monday 1 December 2025 16:00 (1 hour)

Quantum tunnelling is a fundamental process, ubiquitous across nature and technology, with a prominent role in phenomena ranging from stellar fusion and ATP synthesis to nanoscale electronics. Standard descriptions based on single-particle quantum mechanics (QM) or its relativistic version (RQM) have demonstrated utility, accurately predicting alpha particle decay half-lives across 26 orders of magnitude. However, these frameworks are fundamentally incomplete as they do not account for many-particle effects. The need to incorporate interactions becomes apparent in many-body systems like nuclear fusion, where existing models fall short, accounting for these effects phenomenologically rather than from a fundamental theory.

This project aims to develop a Quantum Field Theoretic (QFT) formalism for tunnelling in interacting fermion (spinor) fields. A key motivation is to investigate how the extension to QFT resolves theoretical inconsistencies in RQM, such as the Klein paradox, by naturally including processes such as pair production. In addition, QFT's precisely validated predictions, such as the electron g-factor's quantum correction, stand as a testament to the value of incorporating interacting field dynamics. The primary goal is a method for calculating QFT scattering amplitudes that extends into the non-perturbative tunnelling regime, thereby allowing an investigation of how interactions modify these amplitudes.

An approach was developed to evaluate the infinite S-matrix expansion for above-barrier fermion scattering, known as channelling. This involved deriving coupled recursion relations for the perturbative series of transmission and reflection amplitude contributions. The resulting non-perturbative, all-order coupled system was shown to extend into the previously divergent tunnelling regime, where the approach reproduced RQM tunnelling amplitudes. Subsequently, an extension of the method was investigated to incorporate leading-order interaction effects via QED-like vertex corrections.

The QFT formalism developed in this work provides a promising foundation for investigating how the quantum vacuum and many-particle dynamics influence tunnelling phenomena beyond the limitations of single-particle theories.

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Session Classification: Poster Session

Track Classification: Topical Groups: Theoretical Physics