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Review

# Heavy-ion collisions and fission dynamics with the time-dependent Hartree–Fock theory and its extensions

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ABSTRACT

Microscopic methods and tools to describe nuclear dynamics have considerably been improved in the past few years. They are based on the time-dependent Hartree–Fock (TDHF) theory and its extensions to include pairing correlations and quantum fluctuations. The TDHF theory is the lowest level of approximation of a range of methods to solve the quantum many-body problem, showing its universality to describe many-fermion dynamics at the mean-field level. The range of applications of TDHF to describe realistic systems allowing for detailed comparisons with experiment has considerably increased. For instance, TDHF is now commonly used to investigate fusion, multi-nucleon transfer and quasi-fission reactions. Thanks to the inclusion of pairing correlations, it has also recently led to breakthroughs in our description of the saddle to scission evolution, and, in particular, the non-adiabatic effects near scission. Beyond mean-field approaches such as the time-dependent random-phase approximation (TDRPA) and stochastic mean-field methods have reached the point where they can be used for realistic applications. We review recent progresses in both techniques and applications to heavy-ion collision and fission.

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## 1. Introduction: nuclear quantum many-body dynamics

The quantum many-body problem is vital to many areas of physics. Indeed, the description of complex quantum objects of interacting particles is of interests for many physical systems, from quarks and gluons in a nucleon to macromolecules, such as fullerenes, to Bose–Einstein condensates. Consequently, major developments in the description of quantum many-body systems are often of interest to many different fields. For instance, the BCS theory introduced to describe superconductivity [1] is also widely used in nuclear physics to incorporate the effect of pairing correlations. Similarly, the tools used to study low-energy fusion with multi-channel tunneling [2] are also used to describe dissociative adsorption of molecules on a surface [3].

The similarity between dynamical processes in quantum many-body systems, whether their constituents are nucleons, electrons, or atoms, is quite striking. It is possible to make such systems vibrate, rotate, fuse, transfer particles, fission and break up. This is of course true for nuclear systems, where each of these processes can be used to learn about specific aspects of quantum many-body dynamics. For instance, the study of nuclear vibrations tells us how single-particles can produce collective motion, what is its interplay with the underlying shell structure, what are the source of non-linearities leading to anharmonicities, and how collective modes get damped and decay. These concepts and many others can also be studied via heavy-ion collisions:

- Heavy-ion fusion could be a tool to understand thermalization of a many-body system initially out of equilibrium. Fusion is also well suited to investigate the quantum tunneling of complex systems over orders of magnitudes in terms of barrier transmission probabilities. This allows to study the coupling between relative motion (the main collective degree of freedom used to characterize fusion) with other internal degrees of freedom (vibrations, rotations, single-particle excitations...). These internal degrees of freedom could also be responsible for dissipation and decoherence processes, whose descriptions remain problematic with fully quantal treatments.
- Transfer reactions between heavy-ions are another example of mechanism strongly driven by quantum dynamical processes. Such reactions produce entangled fragments in coherent superpositions of proton and neutron numbers. The measurement of the properties of one fragment (e.g., particle number or kinetic energy) induces a projection of the quantum state of the other fragment. Transfer reactions are also ideal to investigate clustering and superfluidity (via, e.g., the excitation of pairing vibrations). In addition, they are thought to be a doorway to dissipation in heavy-ion collisions. Interesting questions regarding the indistinguishability in the transfer of identical particles could also be raised.
- At higher energies, deep-inelastic collisions (DIC) can be used to investigate quantum fluctuations, via, e.g., the measurement of fragment mass and charge distributions. In addition, dissipation and fluctuations are correlated

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