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The Nuclear Bridge to New Physics: Theoretical challenges in $0\nu\beta\beta$

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The exploration of physics Beyond the Standard Model within nuclear physics is closely tied to the investigation of rare electroweak transitions. The most promising process correspond to the neutrinoless double-beta decay ($0\nu\beta\beta$) which is a transition in nuclei where two neutrons simultaneously transform into two protons, accompanied by the emission of only two electrons [1]. This second-order decay, if observed, would prove that neutrinos are Majorana particles (their own antiparticles), shed light on the existence of massive neutrinos, and help explain the predominance of matter over antimatter in the universe. Understanding this kind of process would unveil important features on neutrino physics, astrophysics and cosmology.
The half-lives depend on the square of the nuclear matrix elements (NMEs), which must be computed since $0\nu\beta\beta$ has not been observed yet.

In this talk, I will present the framework used to compute NMEs and discuss their crucial role in the search for $0\nu\beta\beta$. I will then address higher-order corrections to the NMEs within the nuclear shell model (NSM) and the quasiparticle random-phase approximation (QRPA) frameworks [2]. These calculations aim to reduce the theoretical uncertainties associated with NMEs. Finally, I will briefly present new predictions for two-neutrino double-beta ($2\nu\beta\beta$) transition half-lives, from the 0^+ ground state to the first 0^+ excited state, and discuss their connection to $0\nu\beta\beta$ decay. These results incorporate novel higher-order contributions at the NME level [3,4].

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