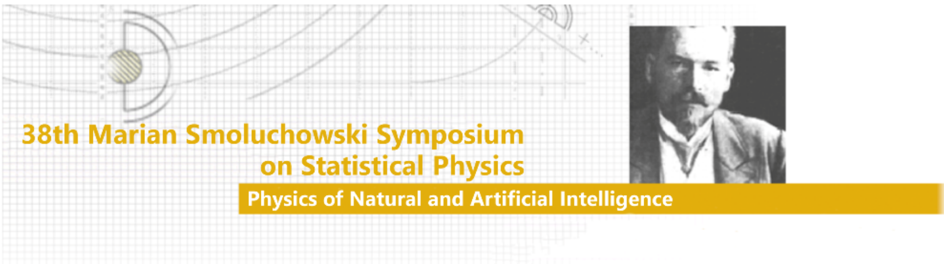

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Entropy-driven adaptation response in far-from-equilibrium living systems: A theoretical model with application to radioadaptation

Monday, 15 September 2025 10:30 (20 minutes)

Living systems are fundamentally thermodynamic structures operating far from equilibrium, characterized by continuous entropy production and driven by external energy fluxes. A key aspect of their long-term viability is their ability to adaptively regulate entropy dynamics in response to perturbations. In this contribution, we present a theoretical framework describing such entropy-driven adaptive mechanisms, with particular focus on the phenomenon of radiation adaptive response (or radioadaptation). This phenomenon is observed in biological systems exposed to low doses or low dose rates of ionizing radiation, enhances repair pathways, modulates apoptosis and cell-cycle control, and stimulates antioxidant production. We construct a general theoretical model in which this response is described as a time- and dose-dependent functions. This yields a dynamic entropy regulation mechanism, derived from first principles of stochastic thermodynamics. We analytically and numerically study the model for two distinct regimes: (1) the priming-dose scenario (Raper-Yonezawa-type effect), and (2) chronic low dose-rate irradiation, relevant for high natural background environments. The model is validated via Monte Carlo simulations and calibrated against available experimental datasets. Beyond its radiobiological relevance, our model generalizes to a broader class of far-from-equilibrium Markovian systems. We demonstrate that entropy stabilization in the steady state emerges from the interplay between external driving forces, potential barrier modulations, and system memory effects. This framework captures key features of adaptive evolution in complex systems and supports the hypothesis that adaptive regulation of entropy production seems to be a universal organizing principle in non-equilibrium statistical physics.

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