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The generalized first law for more general matter

In previous work, a first law of generalized entropy was derived from semiclassical gravitational dynamics around thermal setups using an assumed relation between the matter modular Hamiltonian and the gravitational stress tensor. Allowing for non-minimal coupling between curvature and any tensor matter fields, we show however, that the modular Hamiltonian of thermal states is given by the integrated bulk Noether current associated to time translation plus a spacetime boundary term. One generally cannot express this in terms of gravitational stress tensor components. Still, working with the correct expression for the modular Hamiltonian, we are able to recover a first law of generalized entropy, with added benefits over the previous result. Firstly, any Wald-Dong contributions to generalized entropy resulting from non-minimal coupling between matter and curvature are included. Secondly, in gravitational equations of motion, we allow for a non-vanishing stress tensor expectation value in the unperturbed background and state, and account for background field perturbations as part of its variation. Finally, the quantum matter is allowed to contribute nontrivially to asymptotic energy, e.g. as is necessary, even for a minimally coupled Maxwell field, to recover the expected thermodynamic first law of charged black holes.

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