# Black hole thermodynamics in Horndeski theories

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**Abstract**

We investigate thermodynamics of static and spherically symmetric black holes (BHs) in the Horndeski theories. Because of the presence of the higher-derivative interactions and the nonminimal derivative couplings of the scalar field, the standard Wald entropy formula may not be directly applicable. Hence, following the original formulation by Iyer and Wald, we obtain the differentials of the BH entropy and the total mass of the system in the Horndeski theories, which lead to the first law of thermodynamics via the conservation of the Hamiltonian. Our formulation covers the case of the static and spherically symmetric BH solutions with the static scalar field and those with the linearly time-dependent scalar field in the shift-symmetric Horndeski theories. We then apply our results to explicit BH solutions in the Horndeski theories. In the case of the conventional scalar-tensor theories and the Einstein-scalar-Gauss-Bonnet theories, we recover the BH entropy obtained by the Wald entropy formula. In the shift-symmetric theories, in the case of the BH solutions with the static scalar field, we show that the BH entropy follows the ordinary area law even in the presence of the nontrivial profile of the scalar field. On the other hand, in the case of the BH solutions where the scalar field linearly depends on time, i.e., the stealth Schwarzschild and Schwarzschild-(anti-) de Sitter (AdS) solutions, the BH entropy also depends on the profile of the scalar field. By use of the entropy, we find that there exists some range of the parameters in which Schwarzschild$-$(AdS) BH with nontrivial scalar field is thermodynamically more stable than Schwarzschild$-$AdS BH without scalar field in general relativity. Finally,_˜we consider the Horndeski theories minimally coupled to the $U(1)$-invariant vector field, where BH solutions contain the mass and the electric charge, and clarify the conditions under which the differential of the BH entropy is integrable in spite of the presence of the two independent charges.

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