

Spin-induced Scalarized Black Holes in Einstein-Maxwell-scalar Models

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We construct spin-induced scalarized black hole solutions in a class of Einstein-Maxwell-scalar models, where a scalar field is non-minimally coupled to the electromagnetic field. Our results show that scalar hair develops only for rapidly rotating black holes, while slowly spinning ones remain well described by the Kerr-Newman (KN) metric. The scalar field contributes only a small fraction of the total mass, indicating suppressed nonlinear effects. This suppression may account for the narrow existence domains of scalarized black holes and the similarities observed in their existence domains across different coupling functions. Moreover, scalarized black holes are found to coexist with linearly stable, entropically favored KN black holes. These results motivate further investigations into the nonlinear dynamics and stability of scalarized black holes in these models.

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I. INTRODUCTION

Recently, the LIGO and Virgo Collaborations reported the detection of gravitational waves from binary black hole mergers [1], while the Event Horizon Telescope Collaboration produced the first images of the supermassive black holes M87* and Sgr A* [2–15]. These groundbreaking observations have opened new avenues for testing general relativity in the strong-field regime, including the no-hair theorem, which asserts that stationary black holes are uniquely characterized by their mass, angular momentum and charge [16–18]. However, counterexamples to the no-hair theorem—commonly referred to as “hairy” black holes—have been found in various theories, where black holes possess additional degrees of freedom. The first such solutions were discovered in the Einstein-Yang-Mills theory [19–21]. Subsequently, black hole solutions with Skyrme hair [22, 23] and dilaton hair [24] were also obtained. For a comprehensive review, see [25].

Recently, the no-hair theorem has been challenged by extended theories of gravity that introduce non-minimal couplings between scalar fields and other fundamental fields. A prominent mechanism for circumventing this theorem is spontaneous scalarization, wherein a trivial scalar field configuration around a black hole becomes unstable and evolves into a non-trivial configuration, leading

to the emergence of scalar hair [26–29]. This phenomenon is typically driven by a tachyonic instability, in which scalar field perturbations acquire an effective negative mass squared on the black hole background, triggering growth of the scalar field. In particular, it has been demonstrated that in Einstein-scalar-Gauss-Bonnet (EsGB) theories, a scalar field appropriately coupled to the Gauss-Bonnet invariant can develop a tachyonic instability near Kerr black holes when the spin exceeds a critical threshold [30]. This spin-induced instability has subsequently been shown to lead to the formation of spin-induced scalarized black holes at sufficiently high spins [31, 32].

To gain deeper insight into the dynamical evolution of scalarization, a technically simpler class of models known as Einstein-Maxwell-scalar (EMS) models has been proposed [33]. In these models, a scalar field is non-minimally coupled to the electromagnetic sector, enabling scalarized black hole solutions that go beyond Kerr-Newman (KN) solutions [34–40]. Remarkably, scalarized black holes in the EMS models can exhibit multiple light rings in the equatorial plane [39, 41]. This feature not only leads to distinctive optical signatures in black hole imaging [42–46] but is also associated with the existence of long-lived quasinormal modes [47–51] and potential superradiant instabilities [52].

While most studies of the EMS models have focused on positive scalar-electromagnetic coupling constants—where scalarization is typically driven by electric charge—recent work has shown that, for sufficiently negative coupling constants, rapidly rotating KN black holes can also undergo spontaneous scalarization triggered by a spin-induced instability [53, 54]. Furthermore, the domain of existence for scalar clouds arising from this spin-induced instability has been thoroughly investigated in the KN black hole parameter space [55]. These scalar clouds are generally interpreted as signaling the onset of spin-induced scalarized KN black holes.

In this paper, we numerically construct spin-induced scalarized KN black hole solutions in the EMS models. The structure of the paper is as follows. In Sec. II, we review the EMS models and describe numerical methods used to obtain scalarized black hole solutions. Sec. III presents numerical results for the spin-induced scalarized KN black holes. A summary of our findings is given in Sec. IV. Finally, Appendix A provides a convergence analysis of the numerical solutions, and Appendix B explores the domain of existence for spin-induced scalarized KN black holes with a quadratic coupling function. Throughout this work, we adopt the convention $G = c = 4\pi\epsilon_0 = 1$.