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Nuclear Physics B 934 (2018) 459–465

NUCLEAR PHYSICS B

www.elsevier.com/locate/nuclphysb

Scalar condensation behaviors around regular Neumann reflecting stars

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Received 14 June 2018; received in revised form 18 July 2018; accepted 23 July 2018
Available online 25 July 2018
Editor: Stephan Stieberger

Abstract

We study static massive scalar field condensations in the regular asymptotically flat reflecting star background. We impose Neumann reflecting surface boundary conditions for the scalar field. We show that the no hair theorem holds in the neutral reflecting star background. For charged reflecting stars, we provide bounds for radii of hairy reflecting stars. Below the lower bound, there is no regular compact reflecting star and a black hole will form. Above the upper bound, the scalar field cannot condense around the reflecting star or no hair theorems exist. And in between the bounds, we obtain scalar configurations supported by Neumann reflecting stars.

1. Introduction

The classical black holes describe compact configurations that irreversibly absorb matter and radiation fields at a critical radius known as the event horizon. It was believed that the absorbing horizon leads to the famous no scalar hair theorem that static scalar fields cannot exist around a asymptotically flat black hole, for references see [1–14] and reviews see [15,16]. However, Hod recently found that this no hair property is not restricted to spacetime with a horizon and there is also no scalar hair theorem for regular neutral Dirichlet reflecting stars in the asymptotically flat

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https://doi.org/10.1016/j.nuclphysb.2018.07.021

background [17]. This no hair theorem in the reflecting star background opens up an interesting topic of deriving no scalar hair behaviors in horizonless gravities.

In fact, this no hair theorem also holds in other regular spacetime. In the asymptotically flat background, it was proved that regular neutral reflecting stars cannot support massless scalar fields nonminimally coupled to the gravity [18]. This no hair behavior was also observed in regular asymptotically dS reflecting stars [19]. On the other aspects of black holes, it has been proved in [20,21] that Reissner–Nordström black holes are stable even under charged scalar perturbations in accordance with the no scalar hair theorem of black holes [22]. Very differently, scalar fields can condense around a charged reflecting shell in the limit that the spacetime outside the shell is flat [23,24]. In fact, the existence of scalar configurations doesn't depend on the flat spacetime limit. In a curved gravity, static scalar fields can also condense around the charged Dirichlet reflecting star [25,26]. An interesting property is that hairy Dirichlet reflecting shell and star radii are discrete and have bounds [23,26–28]. One naturally wonders what is the case when imposing Neumann reflecting boundary instead of the above Dirichlet reflecting boundary. At present, charged scalar field configurations were constructed in the charged Neumann reflecting star background on conditions that the star charge and mass is very small compared to the star radius [25]. Along this line, it is meaningful to extend discussions in [25] to construct more general charged hairy Neumann reflecting stars. In addition, it is interesting to search for bounds of hairy Neumann reflecting star radii. And it is also interesting to examine whether there is still no hair theorem for neutral Neumann reflecting stars.

The next sections are planed as follows. In section 2, we show the no hair behavior in the neutral Neumann reflecting star background. In part A of section 3, we provide bounds for radii of charged hairy Neumann reflecting stars. And in part B of section 3, we construct scalar field configurations supported by charged Neumann reflecting stars. The last section is devoted to our main results.

2. The no hair theorem for neutral Neumann reflecting stars

We consider the system of a scalar field nonlinearly coupled to a reflecting star in the four dimensional asymptotically flat gravity. We define the radial coordinate $r = r_s$ as the radius of the reflecting star. And the corresponding Lagrange density of matter fields is

$$\mathcal{L} = -|\nabla\psi|^2 - m^2\psi^2, \tag{1}$$

where m is the mass of the scalar field with only radial dependence in the form $\psi = \psi(r)$.

The spherically symmetric star geometry deformed by matter fields can be expressed as [29]

$$ds^2 = -e^{\nu}dt^2 + e^{\lambda}dr^2 + r^2(d\theta^2 + sin^2\theta d\varphi^2), \tag{2}$$

where ν and λ are functions of r satisfying $\nu(\infty) = \lambda(\infty) = 0$.

From above assumptions, we obtain the scalar field equation in the form

$$\psi'' + \frac{1}{2}(\frac{4}{r} + \nu' - \lambda')\psi' - m^2e^{\lambda}\psi = 0. \tag{3}$$

Near the infinity boundary $r \to \infty$, the scalar field behaves as

$$\psi \approx A \cdot \frac{1}{r}e^{mr} + B \cdot \frac{1}{r}e^{-mr} + \cdots . \tag{4}$$

For massive scalar fields with $m > 0$, the second scalar operator B is normalizable and we fix $A = 0$. So the boundary condition at the infinity can be expressed as