Simple argument for the existence of a semi-stable Planck mass particle

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The existence of a semi-stable particle with a microgram scale mass has been suggested by the study of the possibility of a transition from a black hole to a white hole. Here I give a simpler argument for the existence of this object, relying only on classical general relativity and area quantization.

Consider an isolated spherically symmetric black hole formed by the collapse of a body at some advanced time $v = 0$. Let S_v be the horizon at some advanced time $v > 0$. The following facts are relevant for what follows.

1. The spacetime inside the horizon admits a natural foliation given by the surfaces $\Sigma(v)$ that maximize the volume among all 3d surfaces bounded by S_v. As shown in [1, 2], the volume $V(v)$ of these surfaces grows linearly with v for large v.
2. Hawking's celebrated result suggests that due to the back-reaction of the emitted radiation, the area $A(v)$ of the surface S_v decreases towards zero in a time of order $v \sim m_o^3$ (in natural units $G = \hbar = c = 1$), where m_o is the mass of the body that collapsed [3].
3. Loop quantum gravity predicts the spectrum of any quantity with the dimension of an area to be discrete. The smallest non vanishing eigenvalue of the area in loop quantum gravity is the 'area gap' $A_o = 4\pi\gamma\sqrt{3}$, where γ is the Barbero-Immirzi parameter [4].
4. If the classical evolution between a state a and a state b can only happen in a very long time span, it is reasonable to expect that the amplitude of the same transition in the quantum theory is correspondingly small.

These facts suggest the existence of a semi-stable particle with a mass of the order of micrograms. To see that this is the case, consider an old black hole nearing the end of its evaporation. Because of (2), the area $A(v)$ of its horizon rapidly approaches zero. However, because of (3), it doesn't do so continuously, as the area takes discrete value only. What about the transition to $A = 0$? Before the end of the evaporation, the state on a late stage of the foliation defined in (1) has a very large volume. A transition between a black hole (or its time reversal) with a small internal volume and flat space can happen in short time, but not so a transition between a black hole (or its time reversal) with a large internal volume and flat space. Hence it is reasonable to expect a transition between an old black hole at the end of the evaporation and flat space to be strongly suppressed.

This leaves only one possibility: a long living hole with horizon on a surface with area A_o. This specific conclusion is supported by thermodynamical considerations. Since $A = 0$ is not reachable in short time scales, the system will thermodynamically end up sitting in its lowest (reachable) energy state. For a spherical black hole, the energy depends on the area and minimal reachable energy is minimal reachable area. So the semi-stable state on which the system ends is an eigenstate of the energy, namely an eigenstate of the area. Consequently, the variable conjugate to area, which is the extrinsic curvature, is going to be maximally spread.

Convenient coordinates that include the horizon are the Painlevé-Gullstrand coordinates, in terms of which the metric reads $ds^2 = dt^2 + (dr + \sqrt{2m/r}dt)^2 + r^2 d\Omega^2$. Since in these coordinates the metric is time independent, the extrinsic curvature is the just the derivative of the Lapse function, namely of the metric component $g_{rt} = \sqrt{2m/r}$. This being odd under time inversion, the extrinsic curvature of the time reversal of this metric, namely of a white hole, is the same with a flipped sign. An eigenstate of the intrinsic geometry on the horizon has fully spread extrinsic curvature, hence the quantum state on which the black hole ends up must be such that the metric at the horizon is a quantum superposition of the metric of a black hole and the metric of a white hole.

Similar result, obtained via a more complex analysis of the geometry of a tunnelling between black and white holes were presented in previous literature reviewd in [5], to which I refer for sull refernces and details.

[1] M. Christodoulou and C. Rovelli, "How big is a black hole?," *Physical Review D* **91** (2015) 64046, arXiv:1411.2854.

[2] M. Christodoulou and T. De Lorenzo, "Volume inside old black holes," *Physical Review D* **94** (2016) 104002, arXiv:1604.07222.

[3] S. W. Hawking, "Black hole explosions?," *Nature* **248** no. 5443, (Mar, 1974) 30–31.

[4] C. Rovelli, *Quantum Gravity*. CUP, 2004.

[5] C. Rovelli and F. Vidotto, "Planck stars, White Holes, Remnants and Planck-mass quasi-particles. The quantum gravity phase in black holes' evolution and its manifestations," arXiv:2407.09584. https://arxiv.org/abs/2407.09584.