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Super-Penrose process for nonextremal black holes

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If two particles collide near a black hole, under cerain conditions the energy m_0 in the center of mass frame can become unbounded. This is the so-called Bañados–Silk–West (BSW) effect. Since the discovery of this effect, the main emphasis was made on extremal black holes. Moreover, it was a general belief that this effect takes place for extremal black holes only. Meanwhile, it turned out later that it is possible for nonextremal ones as well. In doing so, one should distinguish between m_0 and the Killing energy of debris at inifnity. For rotating neutral black holes, E is always finite. For charged black holes, say, the Reissner–Nordström (RN) one, E can be unbounded even without rotation. This is called the super-Penrose process (SPP). However, this was found for extremal black holes only.

In the present work, we show that the SPP is possible for static charged nonextremal black holes as well. It is possible also for uncharged ones if some external force acts on particles.

Let us consider the black hole metric

$$ds^2 = -N^2dt^2 + N^{-2}dt^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (1)$$

Let particles 1 and 2 with masses $m_{1,2}$ move from infinity and collide in some point r_c. They produce particles 3 and 4. The energy m_0 in the center of mass frame

$$\begin{aligned} m_0^2 = -(m_1u_1^\mu + m_2u_2^\mu)(m_1u_{1\mu} + m_2u_{2\mu}) = \\ = m_1^2 + m_2^2 + 2m_1m_2\gamma, \end{aligned} \quad (2)$$

where $\gamma = -u_{1\mu}u^{2\mu}$ is the Lorentz factor of relative motion. It follows from the above equations that

$$\gamma = \frac{X_1X_2 - \sigma_1\sigma_2P_1P_2}{m_1m_2N^2}, \quad (3)$$

where $X = E - q\varphi$, φ being the electric potential of a black hole, q particle's charge, P radial momentum.

The outcome of collision depends strongly on the relation between particles' parameters, say, the energy and charge in the RN case. Then, we classify all particles depending on $X(r_+)$, where r_+ corresponds to the horizon. If $X(r_+) > 0$ is separated from zero, a particle is called usual. If $X(r_+) = 0$, a particle is called critical. If $X(r_+) = O(N_c)$, where $N_c \ll 1$, a particle is called near-critical (subscript "c" refers to the point of collision).We assume some nonzero aceleration $a(r)$. For simplicity, we consider pure radial motion. We assume also that particle 1 is near-critical and particle 2 is usual. More precisely, we specify deviation from the criticality in the form

$$b_1(r_+) = E_1(1 + \delta_1), \quad (4)$$

where $b = m\int_r^\infty dr'a(r')$,

$$\delta_1 = C_1N_c + O(N_c^2) \quad (5)$$

with $C_1 < 0$ and in the point of collision r_c we have $N_c \ll 1$. Then, it turns out that in the vicinity of the horizon

$$X_1 = E_1\,|C_1|\,N_c + O(N^2). \quad (6)$$

$$m_0^2 \approx \frac{2\,(X_2)_+\,z}{N_c}, \quad (7)$$

where

$$z = E_1C_1 - \sqrt{E_1^2C_1^2 - m_1^2}. \quad (8)$$

Particle 3 proves to be near-critical. It is the outcome of reaction escaping to inifnity. We obtained

$$X_3 \approx \frac{N_c}{2}(z + \frac{m_3^2}{z}) \approx |C_3|\,E_3N_c. \quad (9)$$

As a result,

$$E_3 \approx \frac{1}{2\,|C_3|}\left(z + \frac{m_3^2}{z}\right). \quad (10)$$

If we choose $C_3 \to 0$, then formally $E_3 \to \infty$ becomes unbounded, as it should be for the SPP. Thus we see that for nonextremal black holes the SPP is indeed possible, provided the coefficient C_3 has to be small.

We showed that a nonextremal static black hole is pertinent to the SPP. In doing so, there is a restriction on a mass escaping to infinity but there is no

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upper bound on its energy. (This holds true as long as backreaction is negligible, so test particle approximation is valid.) Thus the SPP exists both for the extremal and nonextremal RN black hole. Moreover, all this consideration applies even to the Schwarzschild black hole, provided some force is exerted on the critical particle. This includes both any external force or electric repulsive force in the RN metric, if this force is small enough. The latter means that the force does not changes background significantly (that remains approximately Schwarzschildean) but affects particle's motion.

Usually, the electric charge is similar to rotation in black hole physics in many aspects. In particular, this concerns the BSW effect. However, now this similarity breaks down since the SPP does not exist for rotating neutral black holes but is possible for static charged ones. Now, this is seen not only for extremal black holes but also for nonextremal ones.

The key difference between rotating and static black holes and in the context under discussion lies in the role of the centrifugal barrier. One of two new particles after collision should be near-critical. In the first case, this barrier prevents the critical particle with very high energy from reaching infinity after collision that destroys the SPP reach infinity after collision in the first case that destroys the SPP both in the extremal and nonextremal cases. However, for static black holes (say, the RN one) there is no such a barrier at all. The results of the present work extends essentially the area of validity of high energy processes since astrophysically relevant black holes are nonextremal. It is of interest to understand, how the effects of such a kind can reveal themselves in the accretion discs around black holes and for the charge which is not electric but tidal.

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