OPEN ACCESS
Reports in Advances of Physical Sciences
Vol. 8 (2024) 2450001 (7 pages)

DOI: 10.1142/S2424942424500014

World Scientific
www.worldscientific.com

Quantum Entropy and the Mechanism of Gravity

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Received 14 November 2023
Accepted 8 January 2024
Published 5 February 2024
Communicated by Ophir Flomenbom

Quantum entropy measures the number of possible microstates of position and momentum due to quantum uncertainty. Black hole entropy is an example of quantum entropy. Classical entropy, like the Gibbs entropy of a gas, does not depend on quantum uncertainty. This paper is the first to define the quantum entropy of ordinary matter, termed "atomic entropy". The atomic entropy at the surface of a spherical object depends on its mass and is inversely proportional to its surface area. The entropy scale factor (ESF) is a theory that all changes in the scale of spacetime are due to differences in entropy. Defining atomic entropy allows the ESF to make predictions for systems including ordinary matter. In the ESF, gravitational objects are attracted to one another because gravitational entropy, a form of quantum entropy, increases as the distance between these objects decreases. The increase in gravitational entropy increases the total entropy of the system, in accordance with the second law of thermodynamics. This paper is also the first to use the gradients in the scale of space and time predicted by the ESF to derive Newtonian gravity. Explaining the mechanism of gravity in this way provides a link between quantum physics and gravity.

Keywords: Gravity; entropy; general relativity; dark matter.

1. Introduction

Black hole entropy was defined in the 1970s and marked a departure from classical entropy.[1] The event horizon can be described exactly if quantum uncertainty is neglected, so it was initially unclear what black hole entropy could physically represent. When quantum uncertainty is accounted for it is impossible to precisely measure the position and momentum of the black hole, due to information loss from gravitational redshift. One possible physical interpretation of black hole entropy is that it represents quantum uncertainty about the position and momentum of the black hole.[2,3]

Recent research has extended the idea of quantum entropy to objects in gravitational fields (gravitational entropy), to systems of gravitational objects (constellation entropy), and to relative velocity (inertial entropy).[4] These changes have been used to propose that the scale of spacetime changes depending on differences in quantum entropy, resulting in gravity.[3–6] This theory of gravity is called the entropy scale factor (ESF).

This paper explains the difference between classical and quantum entropy and explains how to calculate the quantum entropy of atomic matter. It also describes the mechanism for gravity in the ESF in two complementary ways, one using thermodynamics and the other using quantum physics.

2. Classical and Quantum Entropy

Quantum entropy is defined as entropy due to quantum uncertainty about the location and momentum of particles. Examples of quantum entropy include gravitational entropy (of which black hole entropy is a special case), inertial entropy, constellation entropy and atomic entropy. Classical entropy is uncertainty about the location and momentum of particles that is not due to quantum uncertainty. The Gibbs entropy of an ideal gas is an example of classical entropy.

Changes in scale in the ESF rely on the sum of quantum entropy and the more familiar classical entropy. A theory of gravity cannot be constructed using classical entropy alone, because some objects, like black holes and crystals, can have zero classical entropy but must have a gravitational field. For example, a perfect crystal at absolute zero has zero classical entropy because the arrangement of atoms can be described without ambiguity. These structures must have quantum entropy, however, because the position and momentum of each atom in the crystal are still subject to quantum uncertainty.

Previous papers on the ESF extended the idea of black hole entropy to any object within a gravitational field.[3–6] The rationale for this extension is that a black hole's entropy is due to information loss from gravitational redshift. Since the gravitational field and its resultant gravitational redshift extend outside of the event horizon, other objects within the field should also have some increase in entropy. As with the event horizon, decreased resolution due to gravitational redshift increases the possible microstates of position and momentum. This gravitational entropy of an object outside a black hole is given by Eq. (1), where S_G is gravitational entropy, S_{BH} is the entropy of a black hole, r_S is the Schwarzschild radius and d is the distance between the center of the black hole and the object.[4]

$$S_G = S_{\mathrm{BH}}\left(\frac{r_S}{d}\right)^2. \tag{1}$$

Equation (1) recreates the Hawking entropy of a black hole when r_S equals d, showing that black hole entropy is a special case of gravitational entropy.

Now imagine a thought experiment in which a black hole is divided in half. Since entropy is proportional to the square of a black hole's mass, the entropy of the daughter black holes would each be 1/4 that of the original black hole. The sum of the two black holes' entropy would only be 1/2 that of the original black hole.

In the ESF, however, each daughter black hole would also have gravitational entropy from the other black hole's gravitational field. When the two black holes are touching, the entropy from each interaction is 1/4 the entropy of the original black hole (also given by Eq. (1)). This means that when the black holes touch, the sum of the entropy of the two black holes, plus the gravitational entropy from each black hole being in the other black hole's gravitational field, would add up to the entropy of the initial black hole.

3. Thermodynamics of Gravity

Of course, actually performing the above thought experiment would be impossible because separating the black holes would decrease the gravitational entropy from their interactions, which would violate the second law of thermodynamics.

Now, imagine the inverse situation. Two identical black holes, separated by a distance, with each black hole's intrinsic entropy set to 1/4. In the ESF there would also be gravitational entropy from each black hole interacting with the other's gravitational field. If the gravitational entropy for each interaction started at 0.0001, then the total entropy for the system would start at 0.5002.

What would happen next? Since entropy tends to increase over time, the two black holes would move closer together. This movement would occur because there are more possible microstates of position and momentum for the system as a whole when the two black holes are closer together. This movement would decrease the distance between the black holes, therefore increasing gravitational entropy for the system. As mentioned above, according to Eq. (1), at the point when the two black holes touch the gravitational entropy from each interaction would equal 1/4, the same as that of each daughter black hole. This means that when the two black holes touch, the sum of each black hole's intrinsic entropy plus each interaction's gravitational entropy would equal 1, recreating the Hawking entropy for the combined black hole.

When the two black holes have merged, the system is at its maximum possible entropy, and no further changes occur (neglecting effects like Hawking radiation). How could this single black hole have more entropy than a system of two black holes? Recall that entropy in the ESF measures the number of microstates of position and momentum for the black hole horizon.[3–5] The number of possible microstates increases as the black holes approach each other and reach a maximum in the combined black hole.

4. Mechanism of Gravity

The thermodynamic explanation in the prior section summarizes what happens in gravitational systems, but can gravity be explained on a deeper level, one that offers a quantitative description of gravity?

To do so requires understanding the ESF in greater detail. In this theory, the scale of spacetime changes depending on entropy. For a black hole in empty space, these changes are time dilation and "length dilation" in the radial direction, but not in the circumferential directions.[3–5] Length dilation refers to when a standard length appears longer than it would in empty space, as in Lorentz transformations.

For reference units this paper uses the Planck time and the Planck length. Length dilation from the entropy of a black hole is hypothesized to increase the Planck length by the Schwarzschild radius, for space within the black hole.[3–5] Likewise, time dilation increases the Planck time within the black hole by the time it takes for light to cross the Schwarzschild radius. Outside the black hole, these changes in scale fall off linearly, asymptotically approaching the Planck units in empty space.[4] For spherically symmetric systems, like a Schwarzschild black hole, changes in length and time fall off at the same rate. Changes in the Planck time are shown in Eq. (2), where t_P is the Planck time and t_{P0} is the Planck time in empty space.

$$t_P = t_{P0}\left(1 + \frac{r_S}{d}\right). \tag{2}$$

A black hole in empty space is subject to quantum uncertainty. Repeated measurements of its location or velocity would have variation, but they would cluster around an average value.[3]

Now return to the example of two black holes. What is different in this example is that the quantum uncertainty in the position of each black hole is affected by the changes in the scale of spacetime from the other black hole's gravitational field.

Starting with length dilation, the velocity of black hole 2 would no longer cluster around the same average but would change with time. Standard lengths are longer in the direction of black hole 1, so quantum fluctuations in this direction appear to be larger than fluctuations in the opposite direction. This bias would mean that black hole 2's velocity appears to change in the direction of black hole 1. The rate of change of average velocity due to length dilation would be equal to the gradient in length dilation at black hole 2. According to Eq. (2), this gradient is the Schwarzschild radius for black hole 1 divided by the distance between the black holes. Equation (3) gives the rate of change of velocity of black hole 2 due to length dilation (F_{2-1l}), where r_{S1} is the Schwarzschild radius of black hole 1.

$$F_{2-1l} = \frac{\mathrm{d}(m\mathbf{v})}{\mathrm{d}t} \propto \left(\frac{r_{S1}}{d}\right). \tag{3}$$

Time dilation would also cause a change in black holes' apparent velocities. For black hole 2, time dilation is greater in the direction of black hole 1. Consequently, fluctuations in velocity toward black hole 1 will appear to happen more often than in the opposite direction. The rate of change in velocity is proportional to the gradient in time dilation at black hole 2, but it differs from length in that the gradient of time must be converted to length at black hole 2. To do this the increase in Planck time at black hole 1, which corresponds to r_{S1}, is divided by increase in length at black hole 2, corresponding to r_{S2}. The velocity of black hole 2 due to time dilation is given by Eq. (4).

$$F_{2-1t} = \frac{\mathrm{d}(m\mathbf{v})}{\mathrm{d}t} \propto \left(\frac{r_{S1}}{d}\right)\left(\frac{r_{S2}}{r_{S1}}\right) = \left(\frac{r_{S2}}{d}\right). \tag{4}$$

The total instantaneous change in velocity of black hole 2, F_{2-1}, is proportional to the product of the force due to length dilation, and the force due to time dilation, as shown in Eq. (5). Since a Schwarzschild black hole's radius is directly proportional to its mass, the value for this force is proportional to the gravitational force predicted by Newtonian gravity.

$$F_{2-1} \propto \left(\frac{r_{S1}}{d}\right)\left(\frac{r_{S2}}{d}\right) \propto G\frac{m_1 m_2}{d^2}. \tag{5}$$

5. Atomic Entropy

The above equations and prior papers on the ESF allow for calculations involving black holes, but for these calculations to be done in systems with ordinary matter the entropy of atomic matter must be defined. "Atomic matter" is defined as matter made of particles that do not merge when they touch. Atoms fit this definition, but it can also apply to other forms of discrete matter, like the neutrons in neutron stars.

The shell theorem and tests of gravity tell us that spherical atomic objects behave as if all of their mass was concentrated at a point at the center. Therefore, the entropy of an atomic sphere measured from the outside is the same as if there were a black hole with the same mass at the center of the object. With both black holes and atomic spheres, quantum entropy can only be measured from outside the object, so an atomic entropy measurement from within a sphere can only account for mass between the center and the measurement. For example, the atomic entropy of the earth's core would depend on the entropy of a black hole with the same mass as the core, not the same mass as the earth.

The atomic entropy, S_A, at the surface of a sphere is given by Eq. (6). In this equation r_A is the radius of the atomic sphere, A_{BH} is the area of the black hole and A_A is the area of the atomic sphere.

$$S_A = S_{\mathrm{BH}}\left(\frac{r_S}{r_A}\right)^2 = S_{\mathrm{BH}}\left(\frac{A_{\mathrm{BH}}}{A_A}\right). \tag{6}$$

The entropy at the surface of an atomic sphere will always be less than that of a black hole of the same mass, because the radius of the sphere will always be larger than the radius of the black hole. The difference in size also limits the amount of gravitational entropy the sphere can impart to another object, also given by Eq. (6).

Spherical objects are special because entropy flux is always perpendicular to the surface. Calculating the gravitational field outside non-spherical objects would be more difficult because in this situation entropy flux would not always be perpendicular to the surface. Since astronomical tests of the ESF would likely involve spherical objects, calculation of atomic entropy for non-spherical objects was not attempted here.

6. Discussion and Conclusions

The entropy of black holes was defined years ago.[1] Prior papers on the ESF had described other kinds of quantum entropy, but this paper is the first to define the difference between classical entropy and quantum entropy.[3–6] It is also the first to define the atomic entropy of spherical objects.

The atomic entropy at the surface of ordinary objects, like the sun or the Earth, is much lower than the entropy of a black hole with the same mass, but much higher than their classical entropy. For example, the atomic entropy at the surface of the sun is $\sim 2.6 \times 10^{43}\,\mathrm{JK}^{-1}$. This is much lower than the entropy of a solar mass black hole, $\sim 1.5 \times 10^{54}\,\mathrm{JK}^{-1}$, but it also dwarfs the classical entropy of the sun, $\sim 2.6 \times 10^{35}\,\mathrm{JK}^{-1}$.[7] The large difference between atomic entropy and classical entropy means that classical entropy can be ignored in many calculations.

Many investigators have used the term "quantum entropy", without a consensus on the definition of quantum entropy.[8] Using the same term in this paper risks confusion with other definitions of quantum entropy, such as those measuring quantum information. In this paper, the term "quantum" was chosen because of the centrality of quantum physics to the entropy described and because the proposed difference in entropy parallels the distinction between classical and quantum physics.

This paper also provides a mechanism linking changes in the scale of spacetime to quantum uncertainty, and then uses that mechanism to derive Newtonian gravity for two-body systems. Of course, the ESF will need to be put into relativistic form to explain many observed phenomena of gravity, but its close relationship with Newtonian gravity helps it to explain many simple gravitational systems.

The ESF is limited in that it has not been developed as extensively as alternative theories, like dark matter and dark energy. The predictions of the ESF need to be tested against real-world data, like galaxy rotation curves. The simplicity of this mechanism and the number of physics problems the ESF is related to, including the dark matter phenomena, inflation, accelerating expansion, solar corona heating and relativistic jets, are all reasons that these tests should be performed. The equations listed in this paper may help with these tests.

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