

論文 / 著書情報
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論文要旨

THESIS SUMMARY

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要旨（英文 800 語程度）

Thesis Summary (approx.800 English Words)

In 1916, Albert Einstein proposed the theory of general relativity (GR), which formulates gravity as the dynamics of the geometry of spacetime. A great deal of experimental evidence and observations agree with the predictions of this theory, facilitating its widespread acceptance. One of the most significant observational results of this theory is the prediction of gravitational waves (GW), first observed by the LIGO/Virgo experiments in 2016. As a result, GR is considered a cornerstone of modern physics. In the modern era, GR is considered the most successful theory describing gravitational physics. Despite these successes, there are still several theoretical and observational issues associated with GR that require further investigation. These include the nature of dark matter (DM) and dark energy (DE), the H_0 tension between the cosmic microwave background and late-time observations, the black hole (BH) singularity, the cosmological singularity, and the conflict between renormalizability and unitarity. For these reasons, GR is considered one of the most effective theories to approximate physics beyond the Planck scale. Thus, it is expected that just as Einstein's GR extended Newton's theory in the early 1900s, GR should be extended by some unknown new theory that addresses the aforementioned issues. In fact, many physicists have proposed several theories beyond GR. Today, Metric-Affine Gravity (MAG), or Metric-Affine geometry, is the most comprehensive theory of gravity within the geometric approach. MAG theories describe gravity using two important variables: the metric and the (independent) connection. In this thesis, we focus on this approach to explore beyond GR. In the study of theories in theoretical physics, the concept of symmetry is of great importance. Together with the variational principle, this powerful notion provides a foundation for the success of Lagrange mechanics and other theories in modern theoretical physics. However, at the quantum level, the symmetry of the theory is not always preserved due to the influence of quantum effects. This phenomenon is called a quantum anomaly, which is typically expressed as a violation of classical symmetry at the quantum level. The topic of anomalies in quantum theory, including quantum field theory (QFT), is an important area of research. This thesis focuses on one such anomaly in the context of gravity: the anomaly of the energy-momentum tensor. When the action is invariant under the conformal transformation on the metric, the energy-momentum tensor is observed to possess a traceless property. However, when quantum effects are taken into account, the expectation value of the trace generally acquires a finite value, indicating that the trace anomaly is not zero. When the trace anomaly is caused by the curvature of spacetime, it is called a Weyl anomaly. This type of anomaly represents a significant result of quantum field theory in curved spacetime and has a wide range of applications in theoretical physics. The anomalous trace part represents the quantum effects of matter content on the background spacetime. It is a natural question to ask if there are other similar things happening in different gravitational theories, especially in modified gravity. This thesis investigates the trace anomaly within a general metric-affine geometry that includes both torsion and nonmetricity. The organization of this thesis is as follows. In Chapter 2 and 3, we review the foundations of quantum field theory on curved spacetime and MAG. Along with an affine connection as an extra variable, there is an extra momentum defined by the variation with respect to the affine connection, the hypermomentum. This momentum generally arises in the theory and behaves as another source term in the field equation for MAG. In Chapter 4 we review the standard heat kernel method in QFT on curved spacetime. The trace anomaly is typically computed using the heat kernel method, which is typically used to evaluate a one-loop effective action. The heat kernel method is a useful prescription for evaluating this one-loop quantum effective action on both flat (Minkowski) and curved spacetime. The basis of this method is the asymptotic expansion of the trace of the heat operator, known as the Seeley-DeWitt (SD) expansion. In this context, the expansion coefficients are sometimes referred to as Minakshisundaram coefficients, especially in the field of differential geometry. We introduce Seeley's algorithm, which provides a systematic approach to computing these coefficients for any spacetime. In Chapter 5, we discuss the trace anomaly in the context of MAG theories. We compute the SD expansion for arbitrary spacetimes in the framework of metric-affine gravity, including for the first time the effects of nonmetricity and torsion tensors. We then compute the trace anomaly at the one-loop level in scaling-invariant theories subjected to conformal, rescaling, and projective transformations. For illustration, we study the spin-0 and spin-1/2 cases, considering various interactions between matter and the gravitational sector. It is shown that invariance under the frame rescaling transformation leads to an anomaly in the relation between the hypermomentum and the stress-energy tensor, which arises from the dilation part mediated by the Weyl component of nonmetricity. In contrast, under the projective transformation there is no anomaly; in particular, there is no non-zero trace of the hypermomentum tensor in any of the concrete examples considered. Finally, in Chapter 6, we conclude and mention future prospects.
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備考：論文要旨は、和文 2000 字と英文 300 語を 1 部ずつ提出するか、もしくは英文 800 語を 1 部提出してください。