

# Homework 14 (Due at class on Dec 29)

## 1 Surface gravity

Section 6, Problem 4 [Wal10].

## 2 Cardy formula

### 2.1 Free boson

Let us consider the torus partition function of bosonic string theory

$$\begin{aligned} Z(\beta) &= \frac{1}{q} \prod_{s=1}^{\infty} \frac{1}{(1 - q^s)^{24}} \\ &\equiv \sum_{n=-1}^{\infty} d(n) q^n \quad q := e^{-\beta} . \end{aligned} \tag{2.1}$$

As explained in the lecture,  $1/\beta$  can be interpreted as temperature. The degeneracy  $d(N)$  can be obtained from the partition function by the inverse Laplace transform

$$d(N) = \frac{1}{2\pi i} \int d\beta e^{\beta N} Z(\beta). \tag{2.2}$$

We would like to evaluate this integral (2.2) for large  $N$  which corresponds to large worldsheet energy.

For large  $N$ , we expect that the integral receives most of its contributions from high temperature or small  $\beta$  region of the integrand. To evaluate the small  $\beta$  contribution, it is convenient to use S-dual frame

$$Z(\beta) = \left( \frac{\beta}{2\pi} \right)^{12} Z\left( \frac{4\pi^2}{\beta} \right).$$

Using this property, show that (2.2) for large  $N$  can be approximated as

$$d(N) \sim \frac{1}{2\pi i} \int \left( \frac{\beta}{2\pi} \right)^{12} e^{\beta N + \frac{4\pi^2}{\beta}} d\beta.$$

Using the saddle point analysis, show that the leading asymptotic expression for the number of states is

$$d(N) \sim \exp(4\pi\sqrt{N}) .$$

## 2.2 D1-D5-P system

In the lecture, the torus partition function of the long string in the D1-D5-P system is given by

$$Z = \text{const} \left[ \prod_{m=1}^{\infty} \frac{1+q^m}{1-q^m} \right]^4 \equiv \sum \Omega(n) q^n ,$$

Note that the partition function can be written as

$$Z = \left[ \frac{\vartheta_2(\tau)}{\eta(\tau)^3} \right]^2$$

upto some constant. Using the modular property of this partition function, show that the number of states at large D-brane charges is

$$\Omega(n = Q_1 Q_5 Q_P) \sim (Q_1 Q_5 Q_P)^{-\frac{7}{4}} \exp \left( 2\pi \sqrt{Q_1 Q_5 Q_P} \right) .$$

## References

[Wal10] R. M. Wald. *General relativity*. University of Chicago press, 2010.