Field:
Physics incl. High-energy and Astrophysics

Session Topic:
Gravitational Waves

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1. Introduction

It has been almost 100 years since Albert Einstein predicted the existence of gravitational waves, space-time ripples from a faraway galaxy. Recent technology advancements let us say that the first detection of the waves will be realized in the next 5-6 years. It will not be only the most important proof of the general relativity, but also be the beginning of a new astronomy, which would tell us the structure of galaxies, the true history of the early universe, and maybe a way to make a time machine.

It is important to improve the detector sensitivity so that the signal could be distinguished from noise-induced fake signals. The required sensitivity to detect gravitational waves is almost as high as the quantum limit of the measurement that is imposed by the Heisenberg's uncertainty principle. It has been a new research area to explore the possibility of beating the quantum limit, and moreover to put the macroscopic test mass of the detector in its quantum superposition state.

In my presentation, I would like to share the excitement of starting the new science fields that are based on the two important theories in the modern physics. Here in the following sections let us briefly review the configuration of the gravitational-wave detector and how to improve the sensitivity, which is the key to open a vista for the future.

2. Detector configuration

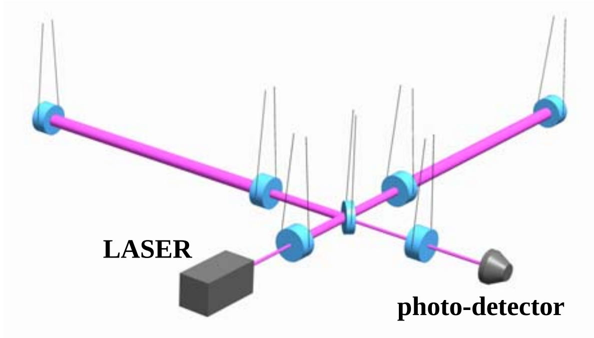

Fig.1: Schematic of a gravitational-wave detector.

Arriving at the Earth, a gravitational wave changes the distance of two objects. The distance expands in one direction and shrinks in the orthogonal direction. As is shown in Fig.1, splitting a laser beam and sending the two beams in the orthogonal directions, one can detect the motion induced by gravitational waves as a differential signal that appears at the anti-symmetric port; here the interferometer is controlled in such a way that all the light returns to the laser (symmetric port). To increase the storage time of the light in the arm, an optical resonator with two high reflectivity mirrors is placed in each arm. An additional mirror is inserted on the way to the symmetric port to enhance the effective power in the interferometer (power recycling). Another mirror is inserted on the way to the anti-symmetric port to enhance the signal fields at desired frequencies (signal recycling). Each optical component is suspended to be free from the ground and to be isolated from the ground motion. The substrate is made of silica or sapphire with a high quality factor coated by low-loss multi-layer films in order to decrease thermal noise.

3. Sensitivity improvement

Figure 2 shows a typical noise budget of a second-generation detector at the room temperature. A Japanese detector LCGT will be operated at 20 K so that thermal noise (TN) will reduce and the sensitivity will be mostly limited by quantum noise.

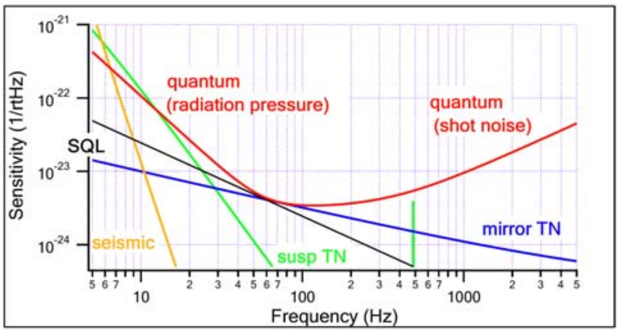

Fig.2: A typical noise budget of a second-generation gravitational-wave detector.

Quantum noise appears in two different ways. Quantum fluctuations of the photon number in the arm cavities cause white force noise called radiation pressure noise and quantum fluctuations at the photo detection cause white sensing noise that is shot noise. Since radiation pressure noise increases and shot noise decreases with laser power, the sum of the two quantum noise curves will not exceed the standard quantum limit (SQL) by simply changing the laser power. However, there exist a number of ways to circumvent the limit. One of them is to readout the quantum fluctuation in the amplitude quadrature and to compensate radiation pressure noise. Another way to overcome the SQL is to configure an opto-mechanical coupling to create an optical spring. These techniques will be installed in some of the second-generation detectors.

4. Toward the first detection

When a signal remarkably larger than the noise curves is detected and the same signal is detected at all the detectors in the world, it will be a strong candidate of gravitational waves. If the source of the waves is a supernova explosion the confidence level will become even higher by the coincidence with neutrinos. Prediction of the waveform with the numerical simulation is also a key to identify signal and noise.

In several years, the second-generation detectors, namely the US detector Advanced LIGO, the French-Italian detector Advanced Virgo, the UK-German detector GEO-HF, and Japanese detector LCGT, will start the operation. Their sensitivity will be ~10 times better than the first generation and will detect a signal more than 10 times per year.

5. Quantum measurement

Exceeding the SQL is a key to improve the sensitivity of gravitational-wave detectors, but how come we can overcome the limit, is there anything wrong in the Heisenberg's principle? The answer is because we do not measure the mass position but the force in the gravitational-wave detector. In some cases the mass is still moving by radiation pressure but we try not to see it. In other cases the mass is more susceptible to the external force so that the sensitivity exceeds the SQL defined for a free mass. It is on the other hand an noble research to focus on the position measurement. To study the quantum behavior of a macroscopic mass will reveal the difference of classical and quantum worlds.