Physics 2213A, Modern Physics Prof. Rick Trebino

Final Exam Spring 2020

Your Name: ____________Yulong Liang______________

Please include your name in the file title also.

1. (8 pts) Falsifiability

a) Should a scientific theory be falsifiable or not? Why or why not?

Yes. Scientific theory must be falsifiable, since its goal is to describe the universe and make predictions, which future experiments could prove it wrong. If people can't even tell whether it is false by observing and deducing, then it is not an effective deduction and can't have the purpose to reveal the truth of the universe.

b) Give an example of a theory (in physics or another field) that is not falsifiable.

Many theories in psychoanalysis, such as having an Oedipal complex, are unfalsifiable.

c) Give an example of a theory in physics that was falsified and what falsified it.

Aether theories. The idea that space can exist by itself without being filled with anything has been under debate since the ancient Greeks, and has been only one idea in a long list of alternatives. The hypothetical matter that fills up "empty" space is generally called aether.

Scientists Michelson and Morley realized that the earth couldn't always be stationary with respect to the aether. They did an experiment with mirror and beam-splitter to find the possible velocity for aether. But no matter what angle they used and performed the experiment all over the world, they always got a null result, which falsified the aether theory.

d) Give an example of a theory that has not been falsified and give two examples of observations that failed to falsify it.

Special relativity. It's the generally accepted and experimentally confirmed physical theory regarding the relationship between space and time. One way to verify this experiment is cosmic ray muons. Muons are produced in the upper atmosphere in collisions between ultra-high energy particles and air-molecule nuclei. But they decay on their way to the earth's surface. Now time dilation says that muons will live longer in the earth's frame, which means that their lifetime will increase if their velocity is large. After the observation at both the top and the bottom of a 2000m mountain, it showed that the number of muons we saw at the bottom of the mountain is bigger than we expected without time dilation, which proves the theory.

Another verification method is atomic clock measurement. Two airplanes traveled east and west, respectively, around the earth as it rotated. The plane traveling west was effectively at rest, while the one going east had a speed of about twice that of the earth's surface. We expected to see the clock in the eastward-flying airplane run slower, and what the result showed matched what we predicted, which proved the theory.

2. (8 pts) The Indian Ocean tsunami of 2004 caused significant damage on the west coast of Sri Lanka, despite the fact that the earthquake that triggered it occurred almost directly east of Sri Lanka, and the tsunami directly struck the east side of Sri Lanka. Provide two physical phenomena that could have played roles in causing this and why.

Seismic waves caused by earthquakes at the epicenter will spread several waves to all directions. It’s possible that two waves made a constructive interference in the direction from the earthquake epicenter to the west coast of Sri Lanka, which combined in phase and formed a wave with high intensity and caused the damage at that place. Another possible physics phenomena is resonance. When we apply a periodic force to a natural oscillator, the result is a forced oscillator. When the seismic wave was at the building's resonance frequency, the oscillation amplitude would be huge and cause damage.

3. (10 pts) Explain Young’s two-slit experiment and its significance for:

a) light in the early 19th century,

Young performed the experiment, when light passed through the double slit experiment. He observed on the screen, at some positions probability density of particles is maximum and at some positions probability density is minimum. It convincely confirmed the wave nature of light. In the early 19th century, scientists thought that light consisted of either waves or particles and they used their observations to debate about that. Young’s experiment showed support to Fresnel’s wave theory and proved that light diffracted precisely, which showed the wave nature of light.

b) particles in the mid-20th century,

In the mid-20th century, scientists thought that particles (electrons) can also have the wave nature. As Young’s method to prove the wave nature of light, scientists thought particles should also exhibit similar patterns when passing through pairs of slits. In 1961, a German scientist succeeded in showing double-slit interference effects for electrons, which demonstrated the wave nature of particles.

c) and very weak light beams again in the mid-20th century.

If we dimmed the light in Young's two-slit experiment, a single photon would show on the screen. Since photons are particles, each can only go through one slit. So at low densities, their distribution should become the single-slit pattern. Somehow, it's as if each electron passes through both slits.

d) What have we learned from these measurements?

From the Young's experiment, we can find that light and particles like photons and electrons all have wave-particle-duality. Scientist Paul Dirac found that each photon acts like a wave (extends over space) at the slits and so interferes with itself to produce the two-slit pattern. Also, in the two-slit experiment, when we are making a measurement, use the particle description. Otherwise, use the wave description. Bohr said it's not possible to describe physical observables simultaneously in terms of both particles and waves.

4. (8 pts) Atoms

a) How did physicists first determine that the positive charge in an atom is concentrated in a small region in the center?

Scientists Rutherford, Gieger and Marsden conceived a new technique to measure how an alpha particle beam is scattered when it strikes a thin metal foil. When he shot a beam of alpha particles at a sheet of gold foil, a few of the particles were deflected. He concluded that a tiny, dense nucleus was causing the deflections. Also, in another experiment, he measured the angle of those scattered alpha particles and the result showed that many alpha particles were scattered from thin gold-leaf targets at backward angles greater than 90 degree. This clearly implied that there was a central hard object inside atoms.

b) How do we know that a solar-system-like model, in which the electrons orbit the nucleus as planets do around the sun, is wrong?

If we consider atoms as a planetary system, the electron will have a centripetal force with the direction to the center of the atom. Also, the planetary atom's electron will emit a light wave at its orbital frequency. Since an accelerated electric charge continually radiates energy (electromagnetic radiation), the total energy must continually decrease. So the electron radius must continually decrease and eventually crashes into the nucleus, which is obviously not possible. So the solar-system-like model for the atom is wrong.

c) How did Niels Bohr solve this problem?

To remedy the stability problem, Bohr modified the Rutherford model by requiring that the electrons move in orbits of fixed size and energy. Bohr placed the electrons in distinct energy levels. The energy of an electron depends on the size of the orbit and is lower for smaller orbits. Radiation can occur only when the electron jumps from one orbit to another. Bohr also included his correspondence principle, which said that in the limit where classical and quantum theories should agree, the quantum theory must reduce to the classical result.

d) Describe a problem with Bohr's model of the atom. Briefly (in just two or three sentences), how was this problem eventually solved by later physicists?

One of the limitations of Bohr's model is that it couldn't explain that when hydrogen gas was excited in a magnetic field, the produced emission spectrum was split. This was later Solved by accounting for the existence of a tiny magnetic moment of each electron.

5. (8 pts) Why is solving the Schrodinger equation for atoms with more than one electron very difficult? Explain how we approximate the states of such systems. What important principle limits what states an electron can be in, and how does it affect the resulting electron states in an atom?

It involves a potential that has many terms involving the mutual electron repulsion, each proportional to 1/|ri-rj|, where ri and rj are the position vectors of the ith and jth electrons. Also, we need to solve for a complicated function, which has 3N arguments, where N is the number of electrons.

We use hydrogenic states to approximate the atomic states.

The Pauli Exclusion Principle says that no two fermions (electrons) can be in the same state in a system. So only two electrons (one spin up and the other spin down) can be in a given state.

6. (8 pts) What is the ratio of the minimum uncertainties of the velocities of an electron and a proton confined to the same small region? Define the relevant terms you'll need to write an expression for this ratio. Before the discovery of the neutron, it was thought that the extra mass of most nuclei was due to extra protons and electrons inside them. Using your result, explain why electrons cannot exist stably within the nucleus (you probably don't have sufficient numerical data to prove it, but you only need to speculate here).

See the answer on the extra paper.

7. (8 pts) What is blackbody radiation? Give two examples of sources of it. Why is it interesting and important? Why was it a problem for 19th-century physicists? Explain Einstein's model for it in words. Why is it also important in cosmology?

All objects can have the ability to radiate. In general, Blackbody radiation is the light emitted by a hot, black body. It is the thermal electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment, emitted by a black body.

Some examples of sources of blackbody radiation are electric heaters, the stars, the sun and night vision equipment.

It is important for quantum physics and cosmology. It can be applied to many areas, such as lasers and microscopes. It's interesting since it shows a phenomenon which can't be explained by classical physics, which inspires physicists to explore more on energy and especially quantum physics.

In the 19th-century, physicists thought that only two "dark clouds on the horizon" of physics that physicists failed to explain and needed more work on them. One of them was that physicists couldn't use classical physics to explain blackbody radiation, since the experiment data had a huge discrepancy with what we predicted using classical physics.

Einstein made an assumption that in a two-level system, particles will have three processes and three emission rates: spontaneous emission rate (from upper level to the ground level), absorption rate (from state 1 to state 2) and stimulated emission rate (from state 2 to state 1). And in equilibrium, the rate of upward transitions equals the rate of downward transitions.

Blackbody radiation is important in cosmology because all planets can be considered as blackbody, and we can know more information about them using the blackbody emission spectrum. Also, it can be used as the evidence for the big bang, since the early universe was a blackbody and we can track the background radiation with cosmic microwave data in order to find information about the early universe.

8. (8 pts) List the absolutely fundamental particles (as we currently understand them) and give a brief description of them. Which are fermions and which are bosons, and what is the defining difference between these two types of particles?

Leptons(electrons, muons, taus and neutrinos): They have no apparent internal structure and seem to be truly elementary. There are 6 leptons(e−, μ−, τ−, νe, ντ, νμ)and their 6 antiparticles(antileptons). They are fermions.

Quarks(up, down, strange, charmed, top, Bottom): A type of elementary particle and a fundamental constituent of matter. An up quark has a charge of +⅔, and a down quark has a charge of -⅓. There are 6 quarks and their 6 antiparticles(antiquarks). They are fermions.

Leptons and quarks are two most fundamental types of particles if that's what the first question asked about.

Gauge bosons(photons, gluon, z boson, w boson): Gluons mediate the strong interaction, which join quarks and thereby form hadrons. The massless photon mediates the electromagnetic interaction. There are three weak gauge bosons: W+, W−, and Z0; these mediate the weak interaction. They are all barsons.

Higgs boson(Higgs boson): observed by Peter Higgs with the prediction that the differences at low energies is a consequence of the high masses of the W and Z bosons. It is a boson particle.

Fermions have half-integral spin and bosons have integer spin.

9. (8 pts) A “tachyon” is defined as a particle that travels faster than the speed of light and which still obeys the laws of Special Relativity.

a) If a tachyon has a real value for its total energy, what can we say about its mass?

b) Show that, if it were to slow down (but still travel faster than the speed of light), its energy actually increases.

c) Imagine that an observer at rest watches a tachyon speed by at speed v (> c). Show that, if the length of the path traveled and the time interval experienced by the tachyon are real as perceived by the observer at rest, then they are both imaginary in the tachyon’s frame and vice versa.

Do you think tachyons are real or imaginary?

See the answer on the extra paper.

10. (10 pts) Imagine that a collision between two distant black holes 100 million lightyears away emits a gravitational wave in all directions that warps space by a peak amplitude of one part in 10^12 at a distance of one lightyear away from it.

a) What will its distortion of space be when it arrives at earth (neglecting any expansion of the universe)?

b) If the gravitational wave is incident from a direction perpendicular to the plane of a Michelson-interferometer gravitational-wave detector, each of whose arms is 1km long and involves a laser beam with a wavelength of 1* 10^(-6)m, how much will each mirror move, as a result, relative to the interferometer's beam splitter?

c) Approximately what fraction of a Bohr radius is this?

d) And by what fraction of a fringe would the gravitational wave cause the interferometer output fringe pattern to shift?

See the answer on the extra paper.

11. (8 pts) It's currently trendy to propose models of our universe that include other universes, as well, and the result is often called the "Multiverse". One such theory hypothesizes that there are infinitely many "universes", all packed adjacent to each other in space, some expanding and others contracting. This infinite expanse of "universes" (they're not really different universes because, if you had enough time and energy, you could travel to them all) is assumed to have existed forever and, although quite variable from place to place (that is, from "universe" to "universe"), has an overall average scale factor, a, that's constant in time. Explain, using a simple 19th-century argument and simple observations that anyone can make, why this cannot be correct.

If this 'universes' is assumed to have existed forever and seems to form an eternal static state (a constant scale factor for every universe), according to Olber's paradox, we should see a bright sky at night time (since it's been calculated that stars will yield the same irradiance at earth). However, that's not true as long as we see the darkness of the night sky. So this theory is not correct.

12. (8 pts) Here's an interesting parallel-universe scenario that I just made up. Imagine that there is another type of matter that's exactly analogous to the matter that we're composed of, but which only interacts with our matter via gravity. It has its own protons, neutrons, electrons, and photons, for example, which have formed stars and planets within our galaxy, but in interstellar space (in between the stars we know) in a manner analogous to our stars and planets. There's plenty of room in our galaxy for such additional stars and their planetary systems because stars are so far apart. But, because this parallel universe's matter doesn't interact with our matter electromagnetically (and its photons can't be detected), we can't see it.

a) We actually have a name for this matter already; what is it?

Dark matter.

b) How might we detect it?

Although we cannot directly detect or see the dark matter, It's easy to detect the effects of dark matter. Hubble Space Telescope images of galaxy clusters show the effects of gravitational lensing due to dark matter. We can see the thin arcs that are images of distant galaxies that have been compressed and bent by the powerful gravity of the galaxy cluster's dark matter.

c) Assume that each parallel universe has a total mass (mass density, actually) approximately equal to ours. Based on measurements already made of our galaxy (and others), how many such universes would there have to be in addition to ours?

Right now our universe only takes 5% of the total universe mass composition, with 23% dark matter and 72% dark energy. If we only consider dark matter as the place for a parallel universe, then approximately 5 parallel universes would there be to fill the missing mass.

d) Describe two observations that imply that this theory is probably wrong (or at least needs to be modified).

One possibility for dark matter is massive compact halo objects. They are failed stars with insufficient density to start nuclear fusion. Searches for gravitational scattering of light by MACHOs have turned up nothing. And the virial theorem says there's not enough anyway.

Another possibility for dark matter is undiscovered elementary particles: Weakly Interacting Massive Particles. They have gravity. They have very weak interactions with ordinary matter and they are very hard to detect. Yet no plausible suggestion exists for the identity of WIMPS. Since both two possibilities for dark matter don't have a strong observation or research to prove them, the theory of dark matter at least needs to be modified.