Questions — PS 303 — Spring 2012

1. **Can you apply the knowledge of quantum mechanics to biology?**

   In 1944 quantum physicist Erwin Schrodinger (Nobel Prize, Physics, 1933) published *What is Life?* The book was based on lectures that he gave at Trinity College, Dublin in February of 1943; it had an influence on several key figures like Watson, Crick and Maurice Wilkins. In the book Schrodinger pointed out that a key feature of the Darwinian nature of inheritance is its basis in discreteness, which could only be explained through quantum discreteness and stability. He argued that these carriers had to be molecules, which we know as DNA. Quantum mechanics explains very small matter like atoms as well as very complicated molecules. But since the human body is made up of around 10^{23} molecules, such a large number means that the use of statistical mechanics is needed as well.

   A recent interpretation of this question has to do with REDUCTIONISM. Leonard Susskind, in his book *The Cosmic Landscape*, states that "Nature seems to be organized in a hierarchical way: big things are made out of smaller things, and so on." Reductionism is the view that the whole is the sum of the parts, and that nature can be understood by reducing it to the simplest components. Steven Weinberg (Nobel Prize, Physics, 1979) is a reductionist, and in his book *Dreams of a Final Theory*, he defines a "final theory" as "the deepest truth from which all other deep truths flow." That is, even if we can't calculate all chemical (or biological) behavior from the quantum mechanics of atoms, we know that the atoms *do* follow those laws, and that is enough. Because quantum mechanics *can* calculate the properties of *simple* molecules means that chemistry works the way it does because of physics. Therefore, even if a final theory is found, chemical and biological laws would still need to be investigated. Weinberg says it best on page 54:

   > "Even though physicists cannot actually explain the properties of very complicated molecules like DNA in terms of the quantum mechanics of electrons, nuclei, and electric forces, and even though chemistry still survives to deal with such problems with its own language and concepts, still there are no autonomous principles of chemistry that are simply independent truths, not resting on deeper principles of physics."

   For the opposite point of view, read "More is Different," by Philip Anderson, *Science* **177** 393-396 (1972). See the course web page for a link.

   — Kevin Chen

2. **What is the BCS Theory?**

   BCS stands for "Bardeen-Cooper-Schrieffer," the three physicists who developed the first quantum theory of superconductivity. In 1911, Dutch physicist Heike Kamerlingh Onnes discovered superconductivity, which is a phenomenon characterized by zero resistance through certain metals when they are cooled to temperatures lower than a critical temperature, T_c. In 1956, John Bardeen received a Nobel Prize in Physics (along with William Bradford Shockley and Walter Houser Brattain) for the discovery of the transistor effect in semiconductors. In 1957, Bardeen created a team with Leon Cooper and Robert Schrieffer and together they developed a microscopic theory for superconductivity known as the BCS Theory. This theory revolves around the concept of Cooper pairs, which is where the attraction of electrons with opposite spin in metals generates a binding energy strong enough to keep the electrons paired at extremely low temperatures. These Cooper pairs are bosons (whereas single electrons are fermions) and thus are allowed to be in the same ground state, which is responsible for the superconductivity. At higher temperatures, though, thermal energy is enough to break the pairs apart, and the metal loses its superconducting properties. Furthermore, since resistivity is inversely proportional to conductivity, as resistivity approaches zero, conductivity approaches infinity. In 1972, the three men won a Nobel Prize in Physics for their accomplishments.

The classical theory of resistance treats current as due to flowing electrons passing through a resistive medium and reaching a "terminal velocity," similar to a skydiver falling through the air. However, this "independent electron approximation" is a complete failure when describing the fact that below T_c, the current in a superconductor shows no discernable decay, and some people have watched for more than 2 years! More than 20 metallic elements can become superconducting, with critical temperatures from mK to 20 K. Many compounds exhibit superconductivity at higher temperatures, on the order of 100 K.

— Krizzy Menez

3. **How are neutrinos detected?**

A neutrino is an elementary particle that is part of the same "family" as the electron, i.e., it's a lepton. The difference is that neutrinos have no electric charge, and also are very light (with a rest energy of less than about 2 eV), which means that they are only affected by the weak nuclear force and the gravitational force. The name neutrino literally means "small neutral one."

The simplest neutrino detector is a vat of chlorine, for example the Homestake mine in South Dakota, which was filled with 470 metric tons of the cleaning fluid tetrachloroethylene, C_2Cl_4. When a neutrino hits a chlorine nucleus, one possible reaction is

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

The fluid is then filtered to find (and count) the number of argon atoms, which directly gives the number of neutrinos that have been captured. Since neutrinos interact only weakly, most pass through the vat of fluid without any interaction. Neutrino detectors, such as the one in the Homestake mine, are often built underground to isolate the detector from cosmic rays and other background radiation.

Other detection methods have been used. For example, the Super Kamiokande detector in Japan observes the Čerenkov radiation* emitted by the neutrinos, and this detector is famous because it was the first to see neutrinos from Supernova 1987A. Also, counting the neutrinos emitted by the Sun have allowed physicists to solve the "solar neutrino problem,"* and determine that the three flavors of neutrinos can spontaneously change into each other.

*Learn about these concepts as part of your outside reading.

— Mitchell Phelps

4. **Why is the Higgs boson so elusive, and why do physicists consider it so important?**

The reason the Higgs boson is so elusive is because it is very massive. One method to create these particles is that used by the LHC in CERN, in which protons and anti-protons collide, annihilate each other, and create other particles. However, the necessary proton kinetic energy to produce a Higgs boson is very large, since the mass of the Higgs is likely greater than 100 MeV/c^2. It has a spin of zero, which is why it's a "boson." The reason why physicists consider it so important is because its properties will hopefully allow us to determine why the elementary particles have the properties that they do, for example, it will help explain why quarks and electrons, along with many other elements, have mass.

The Higgs boson is also known as the "God particle," and currently its existence is hypothetical. Gian Francesca Guidice, in his book *A Zeptospace Odyssey* (ERAU: ebrary), gives this view

> The most inappropriate name ever given to the Higgs boson is "the God particle." Sheldon Glashow gave a much more appropriate definition of the Higgs boson: "Sometimes I compare today's very successful theory of elementary-particle physics with a gorgeous and elegantly crafted mansion. But every residence, humble or grand, must contain an object of no great beauty...The flush toilet is a rather ugly thing, but it works and no one has come up with a plausible alternative." The Higgs boson is like the toilet of the Standard Model edifice. Although indispensable for the functioning of the house, it isn't something that you proudly show to your guests.

An interesting historical account of the development of the ideas leading to the Higgs can be found at `arxiv.org/abs/hep-th/9802142`.

— Katherine Cottingham

5. **Can time be perceived as spatial?**

> *What, then, is time? If no one asks me, I know what it is. If I wish to explain it to him who asks me, I do not know.* – Saint Augustine of Hippo

In short, no. The position of an object in space can follow a functional dependence on time, but the dimension of time is very different from the dimensions of space. Newton was pragmatic and viewed the universe as consisting of "absolute space" and "absolute time," and these dimensions were separate and did not influence each other. This model, of course, was challenged by Einstein who showed that space and time were mixed together, creating a 4-dimensional "space-time." The technical name for this melded structure is MINKOWSKI SPACE-TIME.*

To understand time, we need to distinguish between *events* that take place in time, and *instants* or *moments* of time. (Similarly, to understand space, we need to distinguish between *objects* that exist in space and *locations* of space.) Liebniz claimed that "time is nothing over and above an ordered system of events and that space is nothing over and above a system of objects." (Page 25, *The Nature of Time*, `QB 209.N38 1988`) Newton thought that since space and time were but aspects of God they had their own existence that was separate from objects and events. We shall see that Einstein's theory of special relativity tends to favor the Liebniz view.

A related question that started Augustine on his quest to understand time was "What was God doing before the creation of the world?" An attempt to answer this would lead to a study of cosmology.

— Devon Virden

6. **When an electron in an atom changes energy levels, a single photon is emitted, and when an electron and positron annihilate, two photons are emitted. Is there a way to determine how many photons will come out of a particular reaction?**

   In general, there is no way to be sure how many photons come out of a particular reaction. The answer, as with so many things in quantum mechanics, is probabilistic. However, there are laws that must be obeyed for a particular reaction to be even possible. Namely, not only must energy be conserved, so must momentum as well as angular momentum. As a result of this, pair annihilation cannot possibly emit a single photon. There is no way to conserve both energy and momentum. However, it is possible to emit three photons, depending on the initial angular momentum state. Higher numbers of photons are also possible, but less likely. Similarly, when an electron in an atom decays from one state to another and emits a photon, the above quantities must be conserved. Here, the most likely result is a single photon, and double photon emission is possible, but less likely. Amazingly enough, zero photons could be emitted, but then the energy would have to be absorbed by the kinetic energy of another particle due to a collision. This is called "collisional relaxation." As Abraham Pais writes:

   Is there a theoretical framework for describing how particles are made and how they vanish? There is: quantum field theory. It is a language, a technique, for calculating the probabilities of creation, annihilation, scatterings of all sorts of particles: photons, electrons, positrons, protons, mesons, others, by methods which to date invariably have the character of successive approximations. No rigorous expressions for the probability of any of the above-mentioned processes has ever been obtained.

   — John Li

7. **If electrons and positrons are point particles, how can they collide and annihilate?**

   When an electron approaches a positron (or vice versa), many different things can happen: they can simply scatter from each other (due to the Coulomb force between them), or they can mutually annihilate each other and create other particles (e.g., photons, muons, or quarks). For the electron and positron to annihilate, they must pass close enough and with a small enough kinetic energy so that they "capture" each other. (They don't really capture each other, but they are close enough for the likelihood of annihilation to be significant.) In the scattering event the electron's and positron's kinetic energy and distance between each other is too large for them to annihilate. However, as this occurs they transfer some energy between them and possibly slow down, increasing the likelihood that next time they encounter their antiparticle there will be an annihilation event. Even though the electron and positron do not "collide", their paths are deflected much in same way that the gold nucleus deflects the alpha particle in Rutherford scattering. The difference is that the electron and positron attract. In the case of one of the particles being stationary, the other would take on a hyperbolic path.

These collisions have been used for many years in accelerators to probe fundamental physics. Related to the current question, the effective size of a particle is not always the same as what you might consider the physical size. Let's use Rutherford scattering as an example. The gold nucleus has a radius of 7 fm, and for the α particle to scatter by 90°, Eq (B.4) of the text says that the impact parameter needs to be $b = 22.8$ fm (where I assumed $z = 2$, $Z = 79$, and $K = 5$ MeV). Obviously, the α particle comes nowhere near the gold nucleus. Therefore, in this case, the nucleus's effective size (i.e., the distance at which it has an effect on the projectile) is much larger than its physical size. So, if b is any *smaller* than 22.8 fm the α particle will be deflected by *more* than 90^o. This means that the cross-sectional area for *more* than a 90° deflection is $\sigma = \pi b^2 = 16$ barns.[1] For electron-positron scattering, i.e., $e^- + e^+ \rightarrow e^- + e^+$, the actual process is quantum-mechanical, and is called "Bhabha scattering."[2] If you calculate the classical Rutherford scattering for 90° scattering with $z = Z = 1$ and $K = 10$ MeV, you get $b = 72$ am, which is larger than the measured size of the electron.

The cross section, although it has units of area, is really just a measure of the probability of something happening. At low energies, the dominant process is Bhabha scattering (which at *really* low energies can be approximated by classical Rutherford scattering), but as the energy increases, more things can happen. First, they can annihilate and produce two photons. At even greater energies, they can produce other particles. The plot here `http://pdg.lbl.gov/2002/hadronicrpp_page6.pdf` shows the cross section[3] for the creation of various particles, as a function of total energy of the electron-positron pair. Note that at 0.8 GeV (total energy of both particles in the center-of-mass reference frame) it is very likely that they will create an ω particle. This is a spin 1 meson consisting of up and down quarks (and their anti-quarks), and has a rest energy of 782 MeV. Obviously the creation of this particle requires a minimum energy (called a threshold) of the electron and positron. Also, if you look at the last slide of

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[1] Remember that 1 barn $\equiv 10^{-28}$ m^2.

[2] Take a look at the Wikipedia page for Bhabha scattering which shows the Feynman diagrams involved in this process, and note that they look like Fig 2.3 in the text. As we've talked about, the particles must exchange virtual photons in order to exert a force on each other to cause their deflection.

[3] Note that the scale is in picobarns.

`http://fias.uni-frankfurt.de/~brat/LecturesSS11/Lec_SS9.pdf` to see the cross section for $e^- + e^+ \to \gamma + \gamma$, and note that it decreases strongly with energy, but that at low energies it is very large.

— Finn Carlsvi

8. **How is light affected by gravity when the photons are considered massless? How do black holes affect light?**

Over the past 300 years there has been much debate regarding the dual nature of light. Newton's particle nature of light did not explain the property of interference, and the wave nature couldn't explain experiments such as the photoelectric effect. In 1783 John Michell proposed that a sufficiently large star possesses a strong enough gravitational field which even light cannot escape. A similar conclusion was arrived at by French scientist Pierre-Simon Laplace. Not much was done in the next hundred years because astronomical observations were not advanced enough, and Maxwell's theory solidified the wave nature of light in the minds of most physicists. In 1915, Albert Einstein proposed the theory of General Relativity. Along with quantum mechanics, this theory went on to suggest that though light is composed of photons that are massless, they do possess momentum. Gravity affects light simply because strong gravitational fields alter the shape of spacetime. The photons are then responding to the curvature in this four dimensional spacetime fabric. Since the human brain is not good at picturing things in 4 dimensions we usually resort to an analogy in 3 dimensions. Imagine spacetime as a sheet of rubber, stretched flat when there is no matter present. If we place a massive object like a star in this "space" it pushes down into the rubber sheet creating a dimple or pit in the rubber. An asteroid flying by the star does not appear to travel in a straight line as it rolls along the sheet, but it apparently curves as it passes through the dip, coming out in a new direction. However, the asteroid *is* traveling in a straight line (called a geodesic) locally, it is only the curvature of spacetime that makes its trajectory bend. Light (i.e., photons) have a similar behavior.

The general relativistic prediction for the deflection of light passing near the Sun is twice as large as the Newtonian prediction, which is straightforward and is as follows. We can write the Rutherford scattering equation in the following way:

$$b = \frac{zZ}{2K}\frac{e^2}{4\pi\epsilon_0}\cot\left(\frac{\theta}{2}\right) = \frac{1}{mv^2}\frac{(ze)(Ze)}{4\pi\epsilon_0}\cot\left(\frac{\theta}{2}\right).$$

If we want to obtain the gravitational version of this, we simply make the following replacements

$$\frac{(ze)(Ze)}{4\pi\epsilon_0} \to GMm,$$

where M is the central mass, and m is the mass that is being scattered. That is, the Coulomb electric force constants must be replaced by the Newtonian gravity force constants. The formula for the impact parameter becomes

$$b = \frac{GM}{v^2}\cot\left(\frac{\theta}{2}\right).$$

Note that the mass m of the scattered particle has canceled. All that matters is the speed that it had when it was infinitely far away. If we apply this to light just grazing the sun (that is, let $v = c$, $b = R_{sun}$ and $M = M_{sun}$, then when we solve for the deflection angle we get $\theta = 0.438''$, which is exactly half of the GR prediction, which has been measured during solar eclipses (the first time by Eddington in 1919).[4]

Newton's theory also predicts that if the escape velocity were larger than c, even light could not escape, and John Michell called this a "dark star." In the 20th century, John Wheeler coined the term "black hole." Black holes are celestial objects so massive that no nearby matter or radiation can escape their gravitational field. The point of no escape is called the Schwarzschild radius or event horizon. Often, this is described as the boundary within which the black hole's escape velocity is greater than the speed of light. However, a more accurate description is that within this horizon, all light-like paths (paths that light could take) and hence all paths in the forward light cones of particles within the horizon, are warped so as to fall farther into the hole. Once a particle is inside the horizon, moving into the hole is as inevitable as moving forward in time, and can actually be thought of as equivalent to doing so, depending on the space-time coordinate system used.

— Shankar Nair

9. **What Are Pulsars And Why Do They Emit X-Rays?**

Pulsars are rotating neutron stars, and neutron stars composed solely of neutrons and typically have large magnetic fields. Just like the Earth, the magnetic field is dipolar and has an axis that is not coincident with the spin axis. Electrons in the magnetic field gyrate around the magnetic field lines very rapidly which causes them to radiate (called synchrotron radiation), and this radiation is in the X-ray regime because the electrons have large amounts of energy and X-rays are high energy photons. How do we observe this radiation? Pulsars spin very rapidly, and whereas the sun's period of rotation is roughly once every 30 days, a pulsar rotates about once every 30th of a second. This causes the magnetic axis to be whipped around as the pulsar spins. If Earth is positioned in the direction of this magnetic axis then it appears to an observer on Earth that the pulsar is blinking like a lighthouse. Because the pulses are extremely regular, at first observers thought they were seeing signals from aliens which they called the LGM (little green men) signal.

How do neutron stars form? They are one possible endpoint of a star's life. As a star nears the end of its time on the "main sequence" (defined as the time that it spends fusing hydrogen into helium in its core) it starts to run out of hydrogen atoms to fuse. This causes the hydrostatic equilibrium to lose its balance as the gravitational force takes over temporarily. The star contracts because of this lack of radiation energy from the nuclear fusion reactions pushing out against gravity and therefore core becomes hotter and more dense. The high temperature and density allows helium to "burn," i.e., fuse into carbon, in the core, and the outer layers of the atmosphere also expand, which turns the star into a red giant. This continues until the helium is used up and

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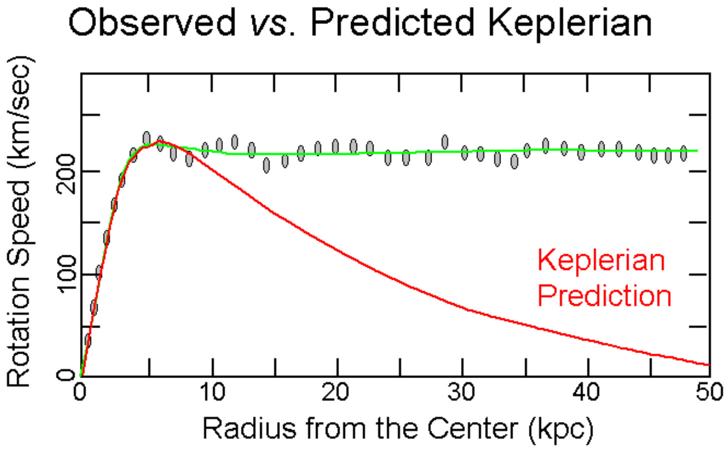
[4] This success was highly advertised, and was instrumental in making Einstein an overnight sensation.

then the star contracts again and switches to carbon fusion and keeps repeating this process of expanding and contracting. This continues until the star gets to iron which is at the peak of the binding energy (per unit mass) curve. Now gravity takes over and the star keeps contracting. If the star is not very massive it will turn into a white dwarf as a result of this gravitational collapse. If the star is more massive it will turn into a neutron star and if it is even more massive then it will turn into a black hole. In a neutron star, all of the protons and electrons are lost so therefore it is made up of neutrons which have a certain amount in each energy level due to degeneracy pressure.

— Amanda Rowen

10. **Why are WIMPs more popular than MOND?**

WIMPs (Weakly Interacting Massive Particles) and MOND (Modified Newtonian Dynamics) are both possible solutions to the problem of "dark matter." Dark Matter is the name given to the cause of the discrepancy between the classical prediction of galaxy rotation rates and the actual observations. The following image describes the difference between the two:



The galaxies must have some additional unseen mass in order to explain these rotation curves. The WIMP hypothesis attributes this mass to very heavy particles (10-1000 GeV range) that only interact through the gravitational force and (possibly) the weak force. On the other hand, MOND suggests that Newton's second law of motion doesn't hold for extremely small accelerations. It suggests that acceleration is not linearly proportional to force at these extreme values. One possible form for Newton's second law is

$$F = ma\,\frac{(a/a_0)}{\sqrt{1+(a/a_0)^2}},$$

where a_0 is determined from observations and is found to be about 1.2×10^{-10} m/s^2. You can see from this form that if $a \gg a_0$ then this becomes our well-loved version, $F = ma$. On the other hand, for small accelerations, $a \ll a_0$, we have $F \propto a^2$, which matches the observed galactic rotation curves very well.

At this point, neither theory has an upper hand. But physicist are reluctant to overturn 300 years of Newtonian physics. And there have been problems making the MOND theory consistent with general relativity. Therefore, it is currently more *fashionable* to support WIMPs rather than MOND when explaining the Dark Matter phenomena.

— Giancarlo Jusino

11. **What is the most widely accepted end-of-universe theory and what is your take on it?**

Which end-of-universe theories could be considered valid strictly depends on which model of the universe they are based. Furthermore, it depends on the assumed "structure" of the universe. There are three such structures — open, closed, and flat — but first we must establish the observation that the universe is in a constant state of expansion; this not to say, however, that the rate of expansion is constant. This rate of expansion is the source of the three structures in discussion.

The rate of expansion of the universe is strictly tied to its mass and energy density. Hence our three possibilities: If the density of the universe were large, gravity would reduce the rate of expansion and in time cause it to reverse its direction (i.e., contraction), which would cause the universe to collapse upon its self. This is theory is popularly known as the Big Crunch and corresponds to the closed universe structure. The second possibility is for the universe's density to be small. In this case gravity would not be sufficient to counteract the rate of expansion and it would continue forever. This infinite expansion corresponds to the open universe structure. The third possibility would be for the universe to posses a critical density which would cause the rate of expansion to approach zero in such a way that it would not collapse upon itself (an asymptotic approach to zero). This is known as the flat universe structure.

However, these three descriptions are based on a universe *without* the so-called "dark energy." Recent observations have confirmed that the rate at which the universe expands is accelerating (thus disproving the possibility of a closed universe) but that interestingly enough its density (including the dark energy density) is close to the proposed critical density value. The current standard model for the universe is the ΛCDM model which stands for Lambda-Cold Dark Matter model. This model attempts to account for all observed large-scale phenomena that have been observed to date. It proposes the idea of dark matter as a means to account for discrepancies between observed gravitational effects of galaxies (and clusters of galaxies) and their corresponding luminous mass, and dark energy as a means to explain the observed accelerating expansion.

In addition to these theories there is also a standing argument for the heat death of the universe, a case where the temperature in the universe would continue to drop as it expands until temperature is the same everywhere (maximum entropy) and work is no longer possible (there is no accessible mechanical energy).

— Francisco Franquiz