1. **The Size of Particle Accelerators**

   The Large Hadron Collier at CERN should accelerate protons to an energy of about 8 GeV

   (a) Given that the protons are constrained to move along a circular path with 9.0 bending magnetic field, use relativistic mechanics to determine the radius of the path. (Hint: What does the strength of the magnetic force depends on? Does the speed of a particle moving in a circle with a fixed energy change? Does its velocity change? Is so, what is the expression for the rate of change of velocity in uniform circular motion?)

   (b) Now repeat the calculation assuming non-relativistic mechanics applies.

   The calculation shows that a non-relativistic machine would be much cheaper. The great size of the LHC (27 km in circumference), is an expensive reminder that relativity is real!

2. **Creating the Z_0**
   The original Super Proton Synchrotron at CERN accelerated protons to an energy of 500 Gev and collided them with protons in a stationary target.

   (a) Calculate the maximum energy available for creating new particles after the collision assuming conservation of momentum and energy. (Hint: you may find it useful to work in the CM frame at first before transforming back to the Lab frame.)

   (b) The energy you found above is not enough to create the Z_0 boson with a mass of 91 Gev. What proton energy would be needed to create this particles

   The engineers at CERN ended up colliding the protons going one way around the tunnel with anti-protons going the other way, thus allowing twice the beam energy to be available for creating particles, and they consequently found the Z_0, and won a Nobel prize. The Z_0 is the mediator of the weak nuclear force. The force is weak because the Z_0 is so massive (and hard to create!)

3. **Forbidden Physics**

   (a) The photoelectric effect is the absorbtion of a photon by an electron with the resulting ejection of the electron from the surface of a metal. However, a free electron cannot absorb a photon. Explain with a diagram showing energy before and after the collision in the CM frame.

   (b) A high energy photon can produce an electron-positron pair if it has enough energy. The process is observed when gamma rays interact with matter, but it can never occur for isolated gamma rays. Explain why using an energy-momentum argument.