Name: ______________________________ Date: ____________________

m_r^β **Physics Practice: Einstein's** *Annus Mirabilis*

In 1905, a relatively unknown physicist named Albert Einstein publish four papers. His paper on Brownian motion provided a strong argument for the existence of atoms. His paper on special relativity explained how the velocity of an observed object affects its observed mass, momentum, energy, size, and time. He wrote a paper equating mass and energy, connecting them with the famous equation $E = mc^2$.

Because we are studying light, we will be interested in his paper on the *photoelectric effect.* It had been known for some time that when light shined on a metallic surface, electrons were sometimes released. What was not understood was the way in which this happened. The light was only released if light of sufficient frequency was used. If the light's wavelength was too long (i.e. the frequency was too low), then electrons were not produced, even if the light was very intense. Einstein determined that energy could only be absorbed by the metal if it came in packets of energy (later called quanta) of a sufficient size. This ushered in the theory of quantum mechanics, and Einstein received the Nobel prize for this paper.

When a high-energy photon is absorbed by an atom, we can detect that the photon has imparted momentum to the atom (or its fragments). This implies that photons have momentum. The classical definition of momentum is $\vec{p} = mv$. However, as far as we know, photons have no mass. Instead of being determined by mass, the magnitude of the momentum of a photon is $|\vec{p}| = h/\lambda$, and the direction of the momentum is the direction of the photon.

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1. What is the momentum of a photon in terms of frequency?

2. A gamma ray photon can have a wavelength that is shorter than the diameter of an atom. What is the momentum of a gamma-ray photon having wavelength 5 picometers?

3. Given that the energy of a photon is $E = h\nu$, derive an expression for E in terms of momentum and the speed of light.