Activity 10: Quantum energy: Mass, energy and the oscillating ruler

Learning intentions

Students can start to understand the relationship between mass and energy expressed in Einstein's $E = mc^2$ and how this helps us understand how the world works and crucially advance our understanding of quantum mechanics and the development of the technologies that come from that.

[This activity has been adapted from Einstein First]

Materials

- 1 flexible plastic 30cm ruler
- Ball bearing (approx 1cm diameter) or similar weighted metal nut that is heavy enough to produce a large frequency change
- Blutak
- Video camera with a slow-motion function (most smart phone cameras have these now)

Teacher Notes	Teaching Notes: Running the activity
$E = mc^2$ indicates the proportional relationship between energy and mass. This is evident even at the quantum scale, a phenomenon recently demonstrated by researchers at the Max Planck Institute (Germany) who showed that photons, even though considered massless can, when absorbed by an atom, add mass to that atom. The atom will lose that mass when the photon is later emitted (*Schüssler R X et al 2020)*. This activity is a classroom version of the experiment that the Max Plank researchers conducted to determine this. In the real experiment, the researchers determined the change in an atom's mass by detecting the change in its vibration frequency when it absorbed or emitted a photon. This change in frequency was a demonstration of $E = mc^2$ because it showed that energy (in this instance, the energy of a photon determined by $E=hf$) will affect mass (in this instance, the mass of an atom). This was a multi-million dollar experiment using highly sensitive equipment. We will use plastic rulers and a small weight to demonstrate how energy affects mass. **What is happening** How did they do it: In short, the researchers had to cool their atoms down to an extremely cold	Method 1. Take your ball bearing (or weight) and using the Blutak attach it to one end of the ruler. It needs to be weakly attached so that it falls off after oscillating the ruler for 20-30 seconds 2. Hold or clamp the ruler firmly to the side of a vertical surface such as the side of a desk 3. Oscillate the ruler horizontally by bending it against the desk (while being firmly held) and releasing the ruler 4. Stand above the ruler and record the oscillation in slow motion. 5. Observe what happens when the mass falls off the ruler when it is oscillating 6. Record your observations and answer the questions in Table 1. Answer the questions in Table 1. At the end of this worksheet. An alternative version: Should you have difficulty getting the weight to leave the oscillating ruler in a way that effectively shows the difference in oscillation frequency, film the oscillating ruler with and

temperature and trap them in a magnetic and electric field to stop them vibrating all over the place and colliding with each other and therefore emitting a whole bunch of different frequencies in the process. Cooled and trapped, the atoms are mostly still emitting a single measurable frequency. The researchers then measure the frequency of the atom after it absorbed a photon then again once that photon was emitted. The atom's frequency is lower when it absorbs the photon and increases when it is emitted. The increased weight of the atom causes its frequency to become lower and this is what the Max Planck researchers measured. Shachar Boublil and David Blair (2023) give a great description of the method the Max Planck researchers used to demonstrate this phenomenon. It is the frequency that is emitted from specific excited atoms (e.g., cesium and strontium) that are the basis of atomic clocks that we use to determine what a second is – see more below. Apart from being the first researchers to successfully measure the miniscule change in the mass of an atoms when it absorbs a photon (as predicted by Einstein, but never demonstrated until now), this demonstrated a new level of precision at measuring quantum effects and as a consequence has opened the door to new ways to increase the accuracy of atomic clocks. Why do we need to do this? Because greater accuracies in how we measure time enable us to measure with greater precision what happens when energy effects a change in a system. Building the most precise timekeepers ever imagined can help unravel big mysteries of our universe such as detecting dark matter and to build the next generation of quantum technologies. Cool fact – the latest atomic clocks are so precise that they are (allegedly) out by just a second every 15 billion years. Read a bit more about [NASA's spin-off tech from better atomic clocks].	without the weight and record your observations.
The Einstein-First Project is a program run by researchers from the University of Western Australia who work with the Gravity Discovery	

Centre, Ozgrav and the LIGO Scientific Collaboration. This project is a part of the Einsteinian Physics Education Research (EPER) team that involves researchers from Norway, China, South Korea, Italy, Germany, Britain and the United States. The Project teaches the fundamental concepts of modern physics to school students and works to improve STEM involvement in the classroom. They have some really cool resources for teachers and students and I encourage you to check them out. https://www.einsteinianphysics.com/	

Table 1. Answer the following questions

What happens to the frequency (number of oscillations) once the mass (ball bearing or nut) flies off?
How does mass affect the frequency? Can you relate this back to Einstein's equation, $E = mc^{2?}$ *In this experiment we only generated changes in the E (energy) and m (mass). What would happen to E if you increased m? Or what would happen to m if you increased E?*