The Atomic Stepladder: Kirchoff's Laws

Objective

Combine conservation of energy with quantization of the atom to explain absorption and emission of spectral lines.

Equipment

Colored stepladder ("atomic energy states")

Colored rod ("continuum energy/color scale")

Colored rubber balls ("photons")

Plastic toy baseball bat ("collisional excitation")

Three plastic tubs ("sun, earth, space")

A willing participant ("atom")

Introduction

Find a willing volunteer from the audience. Ask them if they don't mind making a small spectacle of themselves! You will need their cooperation and to follow your clues as to what to do.

How do we know what the stars are made of? Light from distant objects carries the information to us; we do not have to sample directly. How is this possible? Although it may seem strange or difficult at first, it's really just knowing a few rules and regulations that Nature has imposed upon Herself – and then a bit of common sense to see what those rules imply..

Rule 1: Conservation of Energy

The principle of "there ain't no such thing as a free lunch"; also known as "you can't get something for nothing"; or "the conservation of energy.

Have volunteer step up to first ladder rung. Ask if it took a little energy. Explain that the energy came from "the Cheerios you had for breakfast", temporarily stored as glucose in the body for potential use, then expended in muscle to elevate against gravity. Now have them hop down, explain that the impact on the floor caused heating. Energy was never gained or lost, it only changed forms at each step.

Repeat going to top rung in one step. Ask if it took more energy than before. Have subject hop straight to the ground, ask if s/he felt the greater energy release of landing.

Reinforce the concept that height relates to energy. Reiterate that the first step required a small amount of energy, going to the upper step took a lot more energy. Now ("just to see if you're paying attention"), ask volunteer to expend more energy than the first time, but less energy than the second, and hop up and stay (both feet together) to an intermediate height (indicate with hand a level between the steps). When they balk, reiterate that you're not asking them to work that hard, just "hang at that height".

Allow consternation, then admit that it's impossible. Why? Because the ladder is quantized, so that there are only discrete energies that you can occupy while using the ladder.

Rule 2: Atoms are Quantized

Explain that the stepladder serves as a picture of the structure of a hydrogen atom. The volunteer is the "electron" circling the nucleus (have volunteer walk around the ladder). Explain that while the electron stays in the same energy level of the atom (on this case the "ground state") it requires no energy.

Ask volunteer to step up on first step of the ladder, but as they start to do so, stop them and ask them where they're getting the energy. "Unlike you, atoms don't eat Cheerios for breakfast". Point out that, due to the conservation of energy, they can't get to the first step, because they've already demonstrated that that takes energy, and so are doomed to circle forever at the ground state unless energy comes to them from the outside.

Where can we get the energy? One method is by collisional excitation, being rammed by another atom. Simulate a collision by tapping volunteer with the bat, imparting energy. Have them then step up to first rung … and let them stay there.

Mention that this elevated energy is called an "excited state". Point out that, due to conservation of energy, unless they can find a way to get rid of that energy, they can never jump back down again.

Allow them to step down by suggesting that they can give that energy back to another atom by collisional de-excitation (and allow them to whap you with the bat so as to step back down). Mention that this is how things come to the same temperature (by sharing kinetic energies among the different atoms).

Rule 3: Photons of light carry energy

There are other forms of energy, though, besides the energy of motion of the atoms. Light comes in discrete packets called photons; each photon possesses a specific amount of energy. Show continuum bar, relate height of bar to amount of energy to needed to elevate something to that height. Show color of bar, match photons to it. Explain that color is a biological phenomenon, not a physical one: we perceive different energies carried by photons as different colors, but actually what's "real" is the energy of the photon, not our perception of color.

Now suggest that it's possible for an atom to "swallow" a photon to get to an excited state. Toss a red photon to the volunteer; s/he will usually "get the point" and hold onto the ball while jumping up to the first ladder rung.

After s/he stands there for awhile, ask her how s/he will get back down again. Permit her to hop back down but only if s/he tosses away the red photon again (reiterate: "conservation of energy" at all times.)

Now toss her a blue-green photon (corresponding to the color of the second step). S/he will step to the top ring, and then down again after tossing away the photon.

Now toss her a green photon. If s/he tries to catch it, insist that she float on the ladder at a level between steps. Unless s/he can do so, s/he must realize it's impossible for her to use that photon energy, and s/he must let it pass. Likewise have her "pass" on other photon color balls as well.

The Hydrogen Atom in the Solar Chromosphere

Point out that the atom represented by the ladder is a hydrogen atom, with the red step corresponding to a "first excited energy level", and the red photon with the proper energy to elevate the atom from the ground state to that level is called "Hydrogen-Alpha". The second excited energy state, requiring a blue-green photon, is called "Hydrogen Beta".

[YOU CAN STOP HERE IF YOU WISH, AFTER EMPHASIZING THAT THE VOLUNTEER HAS JUST SHOWN THE BEHAVIOR OF PHOTON EMISSION AND ABSORPTION FROM A SPECTRUM OF LIGHT. OR YOU CAN CONTINUE WITH THE EXPLANATION OF THE SOLAR CHROMOSPHERE]

Now mention that the Sun is primarily composed of hydrogen atoms, and that the stepladder represents a hydrogen atom in the solar chromosphere. Get three more volunteers, one to be the Sun (tub with lots of photons), one to be the Earth (empty earth-tone tub), and one to be "Space or Everywhere Else"), an empty tub with stars.

Set up Sun-Atom-Earth in a straight line, and have Sun "emit" photons of a random color towards Earth. If Atom can't "absorb" a photon because it doesn't coincide with the proper energy for excitation, s/he must let it pass to Earth. Otherwise s/he can absorb it, jump to the proper energy level, and then hop down with re-emission of the photon. But point out that the atom doesn't "remember" which direction the original photon came from, so it is re-emitted in any random direction. "For neatness sake, toss it to Space, which represents any and all random directions except for the direction of the Earth".

Allow photons of random colors to be emitted (and interacted with) for awhile, until enough have been processed to make the final point. Pull out all of the colored balls received at Earth, and point out that there are all the colors of the rainbow present except for two colors. The missing two colors are red and blue-green, and show up in the solar spectrum as absorption lines. Pull out all of the colored balls received in Space, and show that all are either just red or blue-green, with no other colors present. Thus, these discrete lines are emission lines. Finally, re-emphasize that no energy was gained or lost, it was just shuffled around in direction by the chromosphere "atom".

Finally, point out that this is what we see in real life: the Earth observer sees the absorption spectrum when looking directly at the Sun; but when looking slightly to the side of the edge of the Sun (a Space view), one sees the chromosphere in emission. And the color of the chromosphere (literally, meaning "sphere of color") is pink: the combined glow of the red and blue-green Hydrogen-Alpha and Hydrogen-Beta emission lines!