Elementary, My Dear Watson! – Quantum Numbers

Commentary

In the activities below, we will use a pegboard and rubber bands (similar to a Geoboard™ toy) to explore the concepts of energy levels, degeneracy, use of models, and quantum numbers. You may find that your preconceived notion of the atom (assuming you were taught the same middle school curriculum using the same texts/materials most are) is challenged here! Bohr had his day, but it is time to move on to something more sophisticated.

A comment here about models and indirect observation: Models are important in that they provide us with a useful tool for understanding how things work and the ability to make predictions. They may also make life a bit simpler. They should not always be taken literally, however. The Bohr Model of the atom is a perfect example. "Invented" at the beginning of the 20th Century to explain the wavelengths of spectral lines, it served its purpose.

Atoms are not really composed of little spherical electrons circling about a nucleus made of tightly packed balls called protons and neutrons! That model was based on the solar system and had the ability to make some reasonably good predictions, but once one moved along the periodic table to elements more complicated than Hydrogen, something went wrong. Refinements had to be made. Scientists later observed that when spectra were observed for atoms in a magnetic field, what was one line now became two!

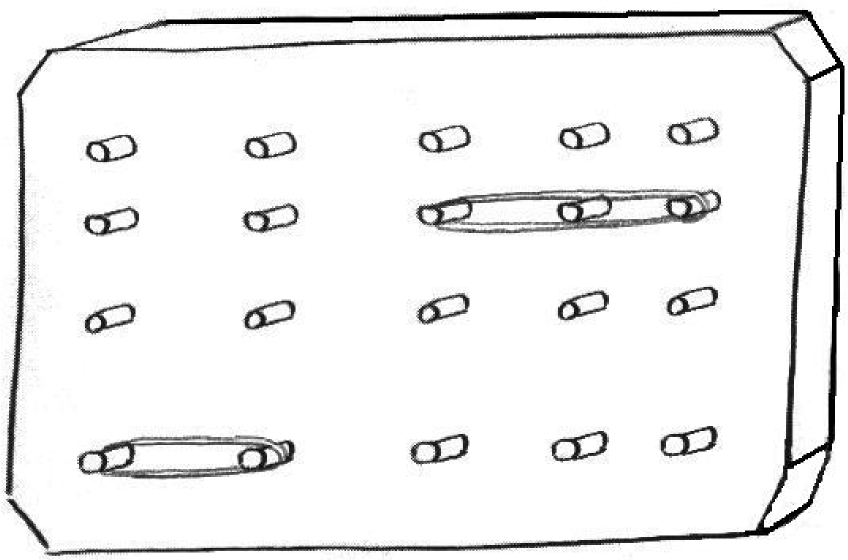
How could electrons have more than one energy if they belonged to a certain energy level, or orbit? This model also has historical significance in that it represents a good start at establishing the field of study called quantum mechanics, or wave mechanics, which is the formalism required to study and understand the behavior of very tiny things, like electrons, atoms, elementary particles, even computer chips. We now know that things like protons and neutrons aren't simple spheres at all, but collections of even smaller things called quarks and gluons. More models keep coming along, each more sophisticated than the preceding one.

We are actually prohibited by Nature from ever looking DIRECTLY into an atom or seeing an electron, yet we believe in their existence. We must use indirect probes. Anyone who ever tells you that he/she knows what an electron IS is sadly mistaken. A physicist can tell you that we know about the PROPERTIES and BEHAVIOR of such things but we cannot hold them in our hand or put them under a microscope and see them directly. The quantum world is a mysterious one indeed. Each model has its own merits and the funny thing is that the degree of success may depend upon exactly what aspects you want to explain or examine!

Other examples of models include the Ptolemaic Model of the Universe (really the solar system), which was "overthrown" in the course of the Copernican Revolution. The model was certainly inaccurate, with the Earth at the center of things and the sun orbiting around the earth. How silly! BUT, it yielded the correct answers. If you wanted to know the position of the sun and planets among the stars at any given time, it could give you the answer. Was it valid? Not as a literal representation of the solar system, but it did have value in that one could make predictions and "organize" nature. Noel Coward had a famous saying: "You ought to have cats fixed, you know - it makes them so much more companionable!"

Think of other examples of models and list them in your portfolio. How about modeling the behavior of the stock market by analysts to make a profit? Behavior patterns in psychology? How children learn? Predicting the actions of the enemy in warfare? How the human body and all of its miraculous parts work? (We are not as simple as your anatomy book might make it appear, but those models DO enable us to treat disorders and design useful medicines.)

The moral? Life is not simple, and neither is nature! We can do our best to make things understandable, however, and often that means performing experiments and organizing the results so that a pattern emerges and then fitting the results to a model.



Plotting electron energy levels using a quantum board

Inquiry

1. Lay your pegboard, Geoboard or nailboard in front of you and start stretching rubber bands around the pegs. Begin to organize the patterns you see. Let's start by saying that horizontal rubber bands correspond to or represent a certain "***Peg Number state***", according to how many pegs or nails are encircled by the rubber band. Let's also say that the vertical position of the row represents a certain "***Energy Level***"(the higher up, the greater the energy). Thus, we have final states that correspond to combinations of energy level and number of pegs inside. These are quite arbitrary, of course, but Quantum Mechanics allows us to act this way, as long as we stay organized and it all "comes together" in the end, with no loose ends.

- How many different "peg number states" can exist in **any given row** on your board?

- Whoops! You just discovered that a rubber band can encompass 2 or 3 nails or pegs and yet can do so at different locations along the horizontal row (energy level)! Are these states really the same? The answer is yes and no. They might be called **DEGENERATE** states. They are the same in that we defined states by the number of nails enclosed by the rubber band, BUT, we can look directly at the board and if they are in different locations there is a subtle difference between them not accounted for by our original definition. Thus, we must add a NEW Quantum Number, which we might call position. Let's use something like the column number of the leftmost peg as our quantum number.

- Now, begin constructing a table. So far, we have three quantum numbers: energy level, number of enclosed pegs, and left-to-right position. Shall we give them all numbers? Too confusing! Scientists who studied the atom by looking at the spectra, or light given off by excited electrons, decided to use a notation based on capital letters, numbers, lower case letters, etc. They were mainly interested in things like energy level and angular momentum. Particle physicists today have run out of numbers and letters and use terms like **Up, Down, Charm, Strangeness, Truth (Top) and Beauty (Bottom)**, and even **Color**! (A blue Top quark is certainly not oriented up or colored blue, and symbols are used like a Yin-Yang for Strange, a heart for Charm, and so on.) Decide on your own scheme, as long as you can keep track. In your table, show all possible combinations of your three quantum numbers. A matrix-type table works best, similar to the shortened example below (use your own notation for the quantum numbers - symbols of any sort are fine and make as many rows as you need).

ENERGY LEVEL	# OF PEGS ENCLOSED	POSITION

2. Oh, what a tangled web we weave! Do you see any order at all in the table? Perhaps you could regroup things under one subheading, such as energy level, then state, then position. In other words, you could create a HIERARCHY of quantum numbers. The final STATE consists of a combination of three quantum numbers, one from each column. If you take a look in a chemistry or modern physics book,

you can see many examples of this form of subdivision. It is sort of like stamp collecting (although the great Earnest Rutherford claimed that physicists never engage in such behavior!). You may remember him if you did the experiment in which you shot marbles under a board to determine the hidden shape – he's the one who determined the upper limit for the "size" of a nucleus. Redo your table so order emerges from chaos, unless you got lucky the first time.

- Which of the enclosed peg # states is the **most probable** (occurs most frequently)? The most probable, lowest energy state for an electron is called the ***ground state*** (rather than an excited one).

- Which number of enclosed pegs is the **least probable**?

- A page in a pad of paper can be said to exist in a certain state which specifies its location. What two properties would you use as "quantum numbers" to characterize that state uniquely?

3. So now we understand our board completely, right? Hold on for a minute! What if I turn it upside down or lay it on its side? Doesn't that change my whole table? Atoms, electrons, and protons don't know their orientation unless we stick them in a magnetic field. Rubber bands and pegboards are non-magnetic, so we'll have to rely on spatial orientation. I think you get the point, so we won't do it all over again. If we did put our states into a magnetic field, they might appear to be different (the degeneracy is removed) in that particles like electrons can possess a quantity called SPIN. They don't really spin (we could see them if they did, anyway), but this quantum number gets its name from the fact that spinning charges would act like tiny electromagnets, and these do seem to behave that way.

Nature allows two particles having opposite spin (one up and one down) to actually be in the same place at the same time! Now things are really getting weird. Thus, we might be able to double our entries in the table if we had two rubber bands, say one red and one blue. Each and every combination, or STATE, could contain of two rubber bands (two states for the price of one). We would then have sub-states - a red one and a blue one - distinguishable only by their color, or spin. **Write down the final number of allowed states, including substates, which you can construct**.

4. Things can become even more complex. What if we allowed ourselves to encompass pegs from more than one row in our state? I'll bet you could construct a mess of these! Let's think of this possibility as something called a MIXED STATE. Nature sometimes treats us this way, too. In quantum mechanics, one refers to superposition of states. Particles can actually exist in two different states at one, but we don't know which one they are in until we make a final observation. Schroedinger summed this up in his famous example of a cat in a box.

You can't see into the box. Is the cat asleep or awake (no shaking the box or peeking!)? If the cat is anything like mine, it is probably sleeping. The answer is that it must be both!! When you open the door, you might see it in either state, but you can only see it at that instant. Also, might opening the door have awakened it? (That's another story - you can mess up the quantum world simply by trying to observe it!) There are concrete examples of such behavior using beams of electrons or other particles. Then again, are they really particles or really waves? That also depends upon the experiment itself. They can act like both - yet another quantum mystery.

5. What have we modeled? Nothing very useful, unless rubber bands are important to you. However, we have seen how one can look for patterns in nature and organize results to account for all possibilities. Such a thing was done in the 1970's by a particle physicist named Murray Gell'Man. By plotting two quantum numbers on a graph, something marvelously symmetrical emerges. There was an octet-eight particles lying at the corners of a hexagon and two in the center. (The Gell'Mann Octet should not be confused a musical group.) But wait a minute - some of the combinations corresponded to particles that hadn't even been discovered yet! By using the combinations of

quantum numbers, however, one could predict the energy of the new particle and behold, they were promptly discovered. Who says models can't be used to spot unexpected patterns or make successful predictions? Some of the most powerful discoveries in science have come about using this technique. Models are powerful, but just be careful not to take them too literally.

So what ever happened to Niels Bohr's lowly planetary model that we still use as a symbol for nuclear energy (at least on "The Simpsons™")? It was soon realized that it was far too simplistic, especially when physicists came to realize that moving electrons behave as waves rather than little charged balls. The quantum picture of an atom is more akin to a fuzzball, or a ball of cotton. We are forbidden by the Uncertainty Principle from ever knowing just where the electron is - we can only guess at where it is most likely to be found most of the time. The nucleus is even fuzzier, hidden from our view and defined only as a smaller region in which neutrons and protons reside, perhaps as pairs, perhaps as a small blob, like a drop of liquid. We can assign quantum numbers to their states, as well, but no more than that. We know even less about their constituent parts, and again must rely on indirect evidence for all of our knowledge. In the case of the electrons, the states are determined indirectly by observing interactions with other electrons, magnetic fields, and bundles, or quanta, of light called photons.