UNIT TEN

Atomic and Nuclear Physics

Physics 312 Reading, Addendum to
Hands-On Physics Activities with Real-Life Applications
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10.1 Bohr Model & Atomic Spectra

Students can "look" into the atom with the use of spectroscopy. According to the Balmer formula, the wavelength of radiation emitted from an atom is governed by the following relationship:

$$\frac{1}{\lambda} = R\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$

In visible light (e.g., the Balmer series of hydrogen), this formula can be simplified as follows:

$$\lambda = 364.6\frac{m^2}{m^2 - 4}\,nanometers$$

where m equals 3, 4, 5, etc. Now, using a spectroscope and the relationship

$$n\lambda = d\sin\theta$$

wavelengths of the atomic spectral lines of hydrogen can be found, and from the Balmer formula the various transitions can be identified.

10.2 Statistics & Probability

A long-half-life radioactive source can be measured over the course of time to show that the distribution of the counts takes on a Poisson and then a Gaussian (normal) form as the average count rate increases. The implication of such a distribution shows that the decay process is random.

10. 3 Radioactivity

Radioactivity is of some importance to everyone due to the fact that it can be found just about everywhere – in smoke detectors, in lantern mantels, and even in the air within one's house. Smoke detectors are designed to work with the element Americium; lantern mantels contain Thorium, and household air, especially in some parts of the county, can be contaminated with Radon, the decay product of Radium. Studying radioactivity, therefore, has a real-world application for students to the extent that they need to understanding the products and processes associated with radioactive decay.

10.3.1 Geiger Counter Demonstrations

Using a Geiger counter or similar (e.g. Geiger-Mueller tube), teachers can demonstrate the presence of radioactivity. Common sources of commonly occurring radioactivity are often impressive: radioactive ore or old "fiesta" glassware from Mexico (Uranium), pitch blend (Radium), gas lantern mantels (Thorium), and smoke detectors (Americium). Even the air itself is filled with high-energy charged particles (cosmic rays) produced from deep space stellar explosions. In addition, decay products (secondary or "shower" particles) from these cosmic rays also populate the lower atmosphere. While these observations are impressive themselves, they pale in comparison with more intense radioactive sources such as radioactive cesium, radioactive chlorine, etc.

10.3.2 Cloud Chamber Demonstration

Cloud chamber demonstrations allow students to see first hand the presence of radioactive decay within a substance. Cloud chambers properly set up and filled with alpha emitters (Polonium 210) and beta emitters (Tellurium 204) show the presence of high-energy ejecta most prominently. Because gamma rays (from Cobalt 60 or Cesium 137) have such small interaction cross-sections, they rarely can be seen with the use of a cloud chamber. If the alpha or beta source is intense, it would be helpful to establish a high voltage sweep field that will clear old ionization tracks quickly.

10.3.3 Measuring decay constant and half-life

Measuring the rate of radioactive decay can be quite difficult unless the proper materials are used. Commonly available atomic sources have half-lives on the order of days or hundreds of thousands of years (e.g., Polonium 210 = 1.38 days; Tin 113 = 115 days; Tellurium-204 = 3.8 years; Cobalt 60 = 5.3 years; Cesium 137 = 30 years). A few minutes of observation will not, therefore, reveal any marked rate of decay. Only when radioactive substances with short half-lives are used is it possible to actually notice a substantial rate of decay within a short period of time (e.g. Barium 137m = 2.6 minutes; Indium 113m = 100 minutes). Obtaining isotopes with short half-lives can be readily done with the proper equipment. Union Carbide MINIGENERATOR systems can be used to separate pure samples of radioisotope daughter from mother products. For instance, the Cesium 137 unit can be used to "milk" Barium 137m from a "cow." Tin 113 can be used to derive Indium 113m.These radioisotope generators use a chemical combination of HCL and NaCl (called the eluant) to separate the daughter products from the mother material.

10.3.5 Radioactive shielding

All forms of radioactivity can be shielded. Absorption of alpha and beta particles, and gamma rays can be readily done by introducing various thicknesses of shielding between the source and the counter. For instance, it is typical to determine the half-value-layer of lead for gamma rays. That is, the thickness required to reduce the radiation to half its original intensity is determined by adding successively more layers of lead shielding to a growing “sandwich” of such plates. A graph of intensity versus thickness can be use to determine the thickness of the half-value-layer.

10.3.6 Inverse-square law

By merely measuring the distance between a radioactive source and the sensor, one can get a good measure of the rate at which radioactive intensity appears to change with distance. Such an experiment assumes, however, that the medium through which the particles/photons travel has no effect on the transport of the radiation. Both alpha and beta particles are readily stopped by just a few inches of air. So, the best way to conduct this experiment is with the use of a gamma ray source.

FOR THE TEACHER

While it is usually best to use an inquiry approach when teaching physics, sometimes it is very appropriate to perform a verification lab. Such is the case with the various aspects of atomic and nuclear physics. For instance, it is highly unlikely that students will be able to come up with the Bohr model of the atom through observations. Sometimes models are developed from laws, but due to the complexity of the laws in these areas of physics, it unlikely (but not impossible) that students should be able to derive these models given the limited amount of time available to students.

When dealing with radioactive substances in the classroom, safety cannot be over emphasized. Before working with radioactive substances, teachers should be well versed in the proper procedures and precautions associated with radioactive substances. A quick review of the AAPT Safety Handbook will be most helpful. Teachers should also carefully consider how to safely secure samples, while stored or while being used by students. Radioactive sources should be carefully accounted for both before class and immediately prior to discharging students.

In addition, providing a clear understanding to students that radioactivity is universally present is helpful to getting them to understand that the small extra dose of radiation that they might encounter while studying radiation (so long as safety precautions are properly observed) is little more than they might encounter over the course of an average day, or during a few hours of high-altitude airplane flight. This should help to allay the fears of anyone working around the low-dose radioactive materials typically brought into a class setting.

With the prevalence of radon contamination in the Midwest, would be a worthwhile problem-based learning project to have students learn about radon testing.

10.3.1 Geiger Counter Demonstration

Discussion: Talking about radioactivity without the use of a way to detect and demonstrate it is tantamount to speaking about the number of angels that can dance on the head of a pin as far as students are concerned. Unless students can actually see and visualize radioactive processes, one has to question the worth of even addressing this topic in an introductory physics course. If teachers don't possess a Geiger counter, then efforts should be made to obtain one either through loan (e.g., science safety office at a local corporation, or the local Civil Defense office, or even a fire station or hospital) or purchase (both Vernier and PASCO sell the Geiger-Mueller tube). Geiger counters that produce an audible sound are much more impressive for students than those that only indicate the count on an analog scale or digital readout.

10.3.2 Cloud Chamber Demonstration

Discussion: The cloud chamber demonstration is among the most impressive that students can observe during an introductory physics course. While one cannot directly observe the nuclear processes that result in radioactive decay; one can only observe the results of that process. One need not possess a commercial cloud chamber to demonstrate the effects of radioactive decay; a cloud chamber can be cobbled together from pieces of metal and glass in the appropriate shapes. The best emitters to be used in the demonstration are those that produce alpha particles. These nuclear decay products are much more massive, and produce a better condensate trail. In the same medium, it is easy to distinguish alpha from beta particles. Alpha particle tracks are comparatively short and are much more pronounced; beta particle tracks, while being the opposite, are also frequently observed with little "knots" along the way. Both can the thought of as somewhat similar to "contrails" left behind by the passing of jets. Cloud chambers are not to be confused with bubble chambers. While their principles of operation are basically the same, cloud chambers contain a supercooled vapor while a bubble chamber contains a superheated liquid. A cloud chamber is to be preferred for a classroom demonstration because its supercooled vapor is mostly like to condense on some discontinuity, and once condensation begins, it continues readily by condensing onto droplets already formed. If a cloud chamber possess appropriate conductors, a small electrical field can be set up to sweep away again condensation trails leaving room for new ones to form in a relatively clear region. If a powerful magnet is contained within the cloud chamber (e.g., neodymium), then circular tracks can be demonstrated to show the effect of magnetic fields on charged particles in motion.

10.3.3 Measuring Radioactive Decay

Discussion: The time rate of change of radioactive decay is hypothesized to be proportional to the number of radioactive atoms, N, present in a sample. That is,

$$\frac{dN}{dt} = -\kappa N$$

where the proportionality or decay constant, κ, makes the proportionality an equality. The negative sign infers the fact that the rate of change of the radioactive decay is decreasing with time. Rewriting and solving the equation yields

$$\begin{aligned}
&\frac{dN}{N} = -\kappa dt \\
&\ln(N) - \ln(N_o) = -\kappa t \\
&\ln\frac{N}{N_o} = -\kappa t \\
&N = N_o e^{-\kappa t}
\end{aligned}$$

Hence, the expected form of the radioactive decay will be exponential, assuming that the original hypothesis holds true.

Unfortunately, this relationship is not conducive to how scientists study radioactive decay. All that scientists can observe is the time rate of change of N. Consider the following more useful formulation.

$$N = N_o e^{-\kappa t}$$

where differentiation results in

$$dN = -\kappa N_o e^{-\kappa t} dt$$

Now, realizing that

$$-\kappa N_o = \left(\frac{dN}{dt}\right)_{t=0}$$

because of the fact stated previously

$$\frac{dN}{dt} = -\kappa N$$

It, therefore, can be concluded that κ represents the fraction of the radioactive particles that decay during a unit time period. This last equation can now be written in more useful form suitable to observable measurement related to radioactive decay

$$\frac{dN}{dt} = \left(\frac{dN}{dt}\right)_{t=0} e^{-\kappa t}$$

This particular formulation of the time rate of change of N is critical to the study or radioactive decay and half-life merely due to the fact that we know neither N_o nor κ in the other possible form of the equation derivable from the first and fifth equations of this section,

$$\frac{dN}{dt} = -\kappa N_o e^{-\kappa t}$$

10.3.4 Decay Constant and Half-Life

Discussion: How can the time rate of decay be related to the half-life ($t_{1/2}$) and what is the physical meaning of the decay constant (κ)? Consider the definition of half-life, the period of time required to a radioactive substance to decay to one-half of its original amount.

$$\frac{N}{N_o} = e^{-\kappa t}$$

$$\ln\left(\frac{N}{N_o}\right) = \ln\left(\frac{1}{2}\right) = -0.693 = -\kappa t_{1/2}$$

$$t_{1/2} = \frac{0.693}{\kappa}$$

which shows the relationship between the decay constant and half life.

10.3.5 Radioactive Shielding

Discussion: Now that students know about radioactivity, they undoubtedly will be concerned about health concerns. How do they product themselves from radioactive materials? It is essentially impossible to protect oneself from ambient background radiation, with perhaps the single exception of radon assessment and mitigation in the air of one's home. Because of the inverse-square nature of radiation, isolating oneself from ionizing radiation will prove to be the single best way to avoid contamination. The suggested activity dealing with radioactive shielding should demonstrate effectively to students that alpha particles are readily stopped even with a sheet of paper, that beta particles are a bit harder to stop, and that gamma rays are very difficult to stop because of their vastly different nature – radiation, not particulate matter.

10.3.6 Inverse-Square Law

Discussion: Like light and sound radiating from a point source, as particulate matter radiates outward into 3-dimensional space, intensity diminishes with the square of the distance. This is merely due to the geometry of space. As radiation passes outward through successive shells of space, the surface area of those shells increases with distance squared. With the same amount of particulate matter (or energy) passing through successive layers, the energy and particle densities drop with the corresponding increase in surface area. Hence, radiations of all types (emanating from point sources) have an intensity that goes with the inverse-square of the distance. So it is with radioactive sources. In completely non-impeded (empty) space, the drop off in intensity goes with the inverse-square of the distance like light and gravity. The rate of drop off goes at an even more precipitous rate if the medium through which the radiation passes can absorb some of the passing radiation. Alpha and beta particles especially are prone this increased form of dissipation. Gamma rays, having a small "cross section," go on their way with little impedance. Hence, to demonstrate the inverse-square law of radiation, teachers would best us gamma sources.

10.3.7 Radon Testing

Discussion: Radon testing is important in Illinois. In fact, Illinois laws dealing with the sale of housing now requires that radon testing take place before any sale, and that identified problems be abated (corrected) before residential properties are sold. Simple charcoal-based collectors are placed within a house for 24 hours. They absorb radon from the air, and are later tested to determine radon content within the household's air. Basements in particular are prone to high concentrations of dangerous radon gas. Houses that are airtight are also prone to high concentrations of radon gas. Ventilating systems are used to draw air out from beneath buildings and are vented to the outside. Individuals living in polluted homes are subject to lung diseases due to the presence of high doses of radon. Living in radon-filled house has the same effect on health as smoking. Depending on the dose received by dwellers in that house, the effect could be the same as several cigarettes to several packs of cigarettes (each pack containing 20 cigarettes) per day.

10.4 RADS & REMS

Discussion: Two systems of measurement for the dose of radiation absorbed by a body exist. The older system measures doses in units called rads. Rad stands for "radiation absorbed dose." One rad is produced when 1 gram of material absorbs 100 ergs of energy. A typical dental X ray, for example, exposes the patient to about 0.25 rads. Because different types of radiation (alpha, beta, gamma) produce different effects at the same dose, scientists now include a quality factor as part of the impact assessment depending upon the nature of the source. The quality factor indicates how much the radiation damages living tissue compared with an equal dose of X rays. For instance, a dose of alpha particles causes about 10 times as much damage as the same dose of X rays, so alpha particles have a quality factor of 10. X rays, gamma radiation, and beta particles have a quality factor of 1. Neutrons range from 2 to 11. Multiplying the dose by the quality factor gives a measure of damage called the dose equivalent. If the dose is given in rads, the dose equivalent will be in rems. One rem (which stands for roentgen equivalent in man) is the amount of radiation necessary to cause the same effect on a human being as 1 rad of X rays. Over a lifetime, a person typically receives 7 to 14 rems from natural sources of radiation, such as cosmic rays. A single exposure of 5 to 75 rems produces few observable symptoms. Vomiting, fatigue, and loss of appetite accompany single exposures of 75 to 200 rems, and recovery takes a few weeks. Severe changes in blood cells and hemorrhage occur with short-term exposures of more than 300 rems. Above 600 rems, additional symptoms include loss of hair and loss of the body's ability to fight infection, usually resulting in death.

Applications to Everyday Life

Cosmic Rays: Cosmic rays are the decay products of dying stars. Each day the Earth is pummeled by trillions of cosmic ray particles coming to Earth from the depths of outer space, probably from the deaths of stars known as supernova events. These primary cosmic rays typically take the form of high-speed atomic particles – mostly beta particles (electrons) and a few alpha particles (helium nuclei). When they encounter atoms and molecules in the atmosphere, they produce a shower of subatomic particles. These secondary particles are readily detected with the use of Geiger counters near the ground. Scientists study cosmic rays because these particles are the only matter that reaches the earth from outside the solar system. Many secondary particles then collide with other atoms, making more secondary particles. Some secondary particles even penetrate deep into the ground. No measurable amount of primaries reaches the Earth's surface.

Radon Testing: Many homes in the Midwest contain air that is polluted by airborne radioactive substance known as radon. Radon is the daughter (decay) product of radium, a metallic element found in nearly all soil and rocks. Radon gas is colorless and odorless, and may be an invisible health hazard in certain buildings if present in significant amounts. High concentrations of radon found in some homes can present a heath hazard as bad as smoking several packs of cigarettes each day. The main source of radon gas in household air is the ground beneath basements and crawlspaces. Minor sources include water that comes from wells and building materials such as granite and gypsum that also come from the ground. Some areas have a high concentration of radium in the soil, and Illinois is not at all immune. Two adjoining houses might have substantially different levels of radon gas for any number of reasons.

Radiocarbon Tracers: Radioactive carbon (C_{14}) is used as a “tracer” to study various complex biological processes. In such research, scientists substitute a radiocarbon atom for an atom of a carbon molecule. Then they use a radiation counter to trace the path of the radiocarbon atom through a chemical reaction in an organism. When the proteins or enzymes containing the radiocarbon reach the site where they are utilized, their presence can be detected by the presence of radioactive decay.

Radioactive Treatments: In recent years doctors have been able to prepare small doses of “containerized” radioactive materials that are then implanted in the middle of cancerous tumors. Located at this location, the ionizing radiation slowly kills the surrounding material.

Smoke Alarms: Most smoke alarms work only due to the presence of radioactive Americium. A small chamber open to the air contains the radioactive source. A detector on the far side of the chamber measures the rate of radioactive decay. When dust or smoke particles (which are natural absorbers of Americium’s decay products) enter the chamber and reduce the counting rate, an electronic detection circuit sounds the alarm.

Atomic Weapons: Atomic weapons (not be confused with nuclear weapons) work by the fission of Uranium-235 (as compared to fusing hydrogen into helium as is done in nuclear weapons). Under appropriate conditions of pressure and density, U_{235} will expel neutrons and radiant energy upon nuclear decay. These neutrons can then collide with other nuclei of U_{235} causing a run-away chain reaction that releases vast amounts of energy.

Power Plants: These power plants essentially consist of a controlled chain reaction similar to that found in an atomic bomb. The reactions are moderated, however, by control rods – long posts of neutron-absorbing cadmium. By introducing more and then less of the control rods' lengths into the power plant core, the rate of chain reaction within the core can be decreased or increased at will.

Radioactive Dating: The rate of decay of an atomic substance can be used to date the material in which it resides – assuming that the initial concentrations are known. For instance, radioactive Carbon-14 (half-life of about 5,730 years) decays into stable Carbon-12 at a known rate. Analysis of air pockets trapped in Antarctic ice show that the atmospheric ratio of C_{14} to C_{12} has not changed for hundreds of thousands of years. This being the case, living plants that within the past 50,000 years or so have metabolize CO_2 from the air will have known original ratios of $C_{14}$to C_{12} when they die. Plants that metabolize CO_2 can then be used for carbon dating. Other types of radioactive dating exist: rubidium-sulurium, uranium-lead, cobalt-manganese, etc.