Cloud chamber experiments: alpha radioactivity and magnetic spectroscopy

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There are three major concepts involved in this lab: the basic physical phenomenon of alpha radioactivity, the interesting particle-detector technology called a cloud chamber, and your ability to interact with the alpha decays using magnetic fields and stopping foils.

Alpha radioactivity works by itself; you are given a working radioactive source, which you should read about to understand properly. In Section 1 we explain a little of the physics, but this is not urgently needed to accomplish the lab.

The cloud-chamber basically works by itself, thanks to the PASCO corporation; you need to read about it to understand what you're seeing, but you don't need to reinvent it. In section 2 we explain its physics, including (importantly) a guide (section 2.2) to alpha interactions. In section 3 we give instructions for turning it on. **Important safety information is contained in section 3. Do not proceed without understanding this section.**

The cloud-chamber will allow you to *see* the alpha particles emitted by your radioactive source. Having seen them, you'll have to figure out how to interact with them, and what you can learn from those interactions. Your instructors suggest several lines of inquiry in section 4, but we encourage you to invent your own. It's important to relate what you see in the chamber to the ideas in section on alpha interactions in section 2.2.

1 Background: what is alpha decay?

1.1 Nuclei and nuclear stability

All nuclei are made up up some combination of neutrons and protons, bound together by the (usually attractive) Strong Nuclear Force[1]. Let's clarify some notation: when you see a nucleus identified as ^{210}Po we mean that (a) the nucleus has the charge Z characteristic of polonium, which the periodic table will tell you is 84, which tells you the number of protons; and (b) has a total of 210 nucleons, i.e. $A = 210$, counting both protons and neutrons. From this you can derive that ^{210}Po has $N = 210 - 84 = 126$, i.e. 126 neutrons. Sometimes you will see the atomic number in a subscript, e.g. $^4_2$He or ^{4}He$_2$ indicating $Z = 2$ and $A = 4$ (therefore $N = 2$), but the 2 doesn't convey any information you couldn't have gotten from the He. Some terminology: oxygen is an *element*, ^{16}O is a *nuclide* or *isotope* (the latter is more common in a chemical context, the former in a nuclear context), protons or neutrons are *nucleons*.

Quantum mechanically, this giant proton/neutron bound state has the same of complications as an atomic bound state—the protons and neutrons must have quantized angular momenta within the nucleus, must obey the Pauli Exclusion Principle, etc., which means that the nucleus has a whole has an elaborate shell structure, excited states, etc.. As is true for atoms, some nuclei are more tightly bound than others. Just like a fluorine atom is happier if it gains an electron, a

[1]The underlying law of this force, called QCD, was solved by Frank Wilczek, H. David Politzer, and UCSB's own David Gross.

^{15}O nucleus is happier if it gains a neutron. Just like a Ne^{-2} ion will spontaneously discard one of its excess electrons, a ^{5}He nucleus will spontaneously discard one of its extra neutrons.

To understand which nuclides are stable, it turns out that you don't need the full shell-model details that you'd use for atoms. Stability and instability are governed by questions of binding-energy, and it turns out that a *liquid drop model* does quite well describing most nuclei.

1.2 Alpha decay

Reference: The discussion at `http://en.wikipedia.org/wiki/Semi-empirical_mass_formula` is fairly good. For detailed information about particular nuclei, consult the National Nuclear Data Center at `http://nndc.bnl.gov`.

The total energy of an nucleus can be described using the same terms as the energy of a charged water droplet. Thanks to E=mc^2, anything that contributes to a nucleus's energy will show up as extra (or missing) *mass* This approach yields the Bethe-Weiszacker semi-empirical mass formula. To get the nucleus's total mass-energy, add the following terms:

1. The nucleons in the nucleus each have a rest mass; add Z times the proton mass plus N times the neutron mass.

2. The nucleons are attracted to one another. This contributes a negative binding energy, equivalent to the heat-of-vaporization of water. Subtract A*15.8 MeV.

3. The nucleus has a finite surface tension. The surface tension behaves like a spring whose internal-spring-energy is proportional to area, i.e. to $A^{2/3}$; water droplets become spherical in order to minimize their area. Since it's a positive energy, add $A^{2/3}$*18.3 MeV.

4. Since the whole nucleus is positively charged, every bit of it is repelling every other bit. This is an anti-binding force, hence it makes a positive contribution to the total energyx. In your intro E&M classes, you learned how to calculate the energy required to compress a net q positive charge into a sphere of radius R; you would have gotten $E = \frac{3q^2}{20\pi\epsilon_0 R}$ In a nucleus, $q = Z$ and $R \propto A^{1/3}$; so, to the nuclear mass, add $Z^2/A^{1/3}$*0.714 MeV.

5. There are additional quantum-mechanical terms which we won't discuss here.

The point of this discussion is: consider a supply of water of fixed mass and charge, or a supply of nucleons of fixed A and Z. Suppose you have the option of (a) making a single large droplet, or (b) making two smaller droplets. Look at the terms above: the surface-tension term is made worse (more energy needed) to split the supply into two droplets; it favors the single large droplet. (Can you prove this?) The Coulomb term, however, is made worse (more energy needed) to get all of the charge into one blob; it favors splitting up.

Both *nuclear fission* and *alpha decay* occur when the Coulomb term "wins" over the surface-energy term. The Z^2/A term starts off small, but it grows faster than the $A^{2/3}$ term, and somewhere around $Z = 82, A = 212$ it wins; large nuclei "want" to break up; they benefit more from reducing their Coulomb energy than they lose from gaining extra surface energy.

Fission is a roughly-even breakup, like ^{252}Cf $\rightarrow$ ^{104}Zr + ^{148}Ce. Alpha decay is the emission of a ^{4}He nucleus, AKA an alpha particle. The cloud chamber includes a ^{210}Pb source, a tiny collection of radioactive lead plated onto the surface of a sewing needle. This nuclide undergoes a chain of three decays: with a 22-year half life, it beta decays (^{210}Pb $\rightarrow^{210}$Bi + e$^-$ + $\bar{\nu_e}$). Almost immediately, with a 5 day halflife, the daughter bismuth itself beta-decays (^{210}Bi $\rightarrow$ ^{210}Po + e$^-$ + $\bar{\nu_e}$). With a halflife of 138 days, the polonium then alpha decays (^{210}Po $\rightarrow$ ^{206}Pb + ^{4}He), with the ^{4}He carrying away 5.407 MeV of kinetic energy. These polonium-decay alphas are what you see in the cloud chamber.

1.3 Tunneling

Reference: the discussion at `http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/alptun.html` is good.

Alpha decay is a quantum-mechanical process. If you want to write the Schrodinger equation for an alpha particle, the Bethe-Weiszacker description above sets up the "energy landscape", i.e. the potential $V(r)$, experienced by this particle. This landscape has a barrier: if an alpha particle wanders *just barely outside* the nucleus, it's already fighting the surface-energy effect, but isn't far enough away to mitigate the Coulomb repulsion. The alpha's escape isn't actually a net-energy-benefit until it's gotten far away—maybe 30 fm, or two or three nuclear diameters. Thus, the region between the surface and 30 fm is a *quantum mechanical potential barrier* and the alpha particle has to tunnel through it. The rarity of this tunneling—the low transmission probability, to put it in the terms you'll calculate in a quantum class—is what makes alpha-decay half lives so long. (Think about: the half life of your 210Pb needle is 22 years. Consider a nascent alpha particle that's bouncing around inside the 10-fm-wide nucleus, say with 5.5 MeV kinetic energy, for 22 years. How many times does it "try" hitting the wall, before successfully tunneling out?)

2 The cloud chamber

2.1 Supersaturation, condensation, and nucleation

The bottom plate of the chamber is cold. The top plate is at room temperature. The walls include a "sponge", ensuring that there's liquid alcohol both in the warm region and the cold one. The chamber works because alcohol evaporates from the sponge in the warm region, where the saturation vapor pressure is high. The "wet" air sinks and/or diffuses downward, into a colder region where the saturation vapor pressure is low. To get to equilibrium, this alcohol has to get out of vapor phase into liquid phase—i.e. it has to undergo a phase transition. This is difficult to do in deionized, clean air, so the alcohol spends some time "supersaturated", i.e. with a far-above-equilibrium vapor content. The phase transition occurs easily—a process called "nucleation"—in the presence of free ions. Therefore, we will see sudden droplet nucleation (and growth) at the site of ions in the gas.

What is the saturation vapor pressure of your alcohol at room temperature? At -35C? If you take 1cc of saturated gas at room temperature, and chill it to -35, what *volume* of alcohol needs to condense? Can you use this knowledge, and observation of the density of droplets, to guesstimate the volume of each drop?

Due to the clearing field—the extra few hundred volt potential drop supplied by the yellow cable—there should not be many random free ions in the gas. Since the chamber is sealed, there should not be much dust. The passage of an *ionizing particle* can ionize gas molecules (i.e., separate electrons from molecules, leaving behind ions) and provide a trail of nucleation sites. This is what you're seeing.

2.2 The passage of particles through matter

References: a reasonable layman's discussion is `http://en.wikipedia.org/wiki/Bethe_formula`. The gold standard professional explanation/formulas/etc. are found at the Particle Data Group: `http://pdg.lbl.gov/2012/reviews/rpp2012-rev-passage-particles-matter.pdf`. Valuable data tables are found at NIST: `http://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html`

So, the question relevant to this lab is: how does an alpha particle behave as it travels through this gas? The alpha particle (Z=2, i.e. positively charged) is surrounded by a strong electric field. When it passes near a gas molecule, this electric field (and an associate magnetic field) may be strong enough to ionize the molecule. This necessarily exerts a retarding force, and saps some energy from the passing alpha, needed to both (a) overcome the molecule's ionization potential, and

(b) to give the excised electron some kinetic energy. The more often such ionization happens, the faster the alpha will slow down. We express this in dE/dx, the energy lost per unit distance traveled (units of MeV / cm, for example). If there are more molecules available (say, in a denser gas) then obviously there are more collisions per unit distance; to remove this trivial effect of density ρ, many formulas will report something $(dE/dx)/\rho$ in units of MeV g^{-1} cm^2—watch out for this distinction.

The stopping power (both dE/dx and $(dE/dx)/\rho$) also depends on the material, but only weakly—to a good approximation, stopping is really scattering off of *electrons*, and all materials have approximately 3×10^{23} electrons per gram. In this lab, the difference between air, helium, and CF_4 is mostly a difference in ρ. (Can you show that the "Z/A" term in the Bethe formula makes dE/dx depend on electron density?)

For intermediate energies, i.e. if the alpha's velocity is much faster than a typical atomic electron's velocity, we use the Bethe formula. Interestingly, a slow-moving particle is a much *more effective* ionizer than a fast one; roughly speaking, if the alpha passes slowly, each gas molecule spend more time in the alpha's electric field, and is more likely to feel it. The energy loss per unit distance depends on $1/v^2$. Think about what this means for a particle starting off at $v = 0.02c$ and stopping: the alpha zooms along for a centimeter or so with *low* energy loss; then it slows down, $1/v^2$ gets very large, and the energy loss increases; it might lose 1/2 of its energy in the first cm of travel, but dump the last 1/2 in only a mm. This end-of-track stub of dense energy loss is called the "Bragg peak".

There is no simple theory for the shape of the Bragg peak, i.e., the v dependence of dE/dx when the velocities are too low for the Bloch formula. Many different effects are kicking in: the alpha can now easily pick up an electron (behaving as He^{+1} rather than He^{+2}) for a short time; it can now change direction easily and turn away from the hardest collisions; the gas's dielectric properties have more time to respond and to "screen" the now-slowly-changing electric field of the passing particle. Our best "theory" of alpha stopping comes from an immense phenomenelogical database assembled by Ziegler et. al., and nowadays accessed either through the software SRIM (www.srim.org) or via the NIST ASTAR database.

2.3 Your "^{210}Pb" radioactive source

The cloud chamber includes a ^{210}Pb source, a tiny collection of radioactive lead plated onto the surface of a sewing needle. This nuclide undergoes a chain of three decays: with a 22-year half life, it beta decays ($^{210}\mathrm{Pb} \rightarrow {}^{210}\mathrm{Bi} + e^- + \bar{\nu_e}$). Almost immediately, with a 5 day halflife, the daughter bismuth itself beta-decays ($^{210}\mathrm{Bi} \rightarrow {}^{210}\mathrm{Po} + e^- + \bar{\nu_e}$). With a halflife of 138 days, the polonium then alpha decays ($^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb} + {}^{4}\mathrm{He}$), with the ^{4}He carrying away 5.407 MeV of kinetic energy. (^{206}Pb is stable.) These polonium-decay alphas are what you see in the cloud chamber.

In equilibrium, each decay in this chain occurs at the same rate as the others, even though the inventories (the supply at any moment) of ^{210}Pb, ^{210}Bi, and ^{210}Po are very different. If you're interested, you can (a) prove this mathematically using the principle of detailed balance, or (b) simulate it with coupled differential equations in Mathematica.

3 Basic cloud chamber setup

Safety notice This lab uses three safety hazards: flammable alcohols, radioactivity, and high-pressure compressed gases.

3.1 Turning it on

1. Pour 10-20ccs of the supplied alcohol (isopropanol, ethanol, or methanol will work) through the center hole in the chamber. This will form a puddle at the

Safety: All of these alcohols are volatile, flammable, and toxic if ingested. "Denatured ethanol" is 10% methanol.

bottom, and also dampen the sponge-like blue "curtain" visible at the edge of the chamber.

2. Take a bucket over to the Chemistry Building and fetch ice. The machine is located in an alcove between Chemisty and Physical Science Building North.

3. Locate the water-cooling tubes emerging from the back of the chamber. One of them is connected to a submersible pump, the other to a loose hose which will return water to the bucket. Fully immerse the pump in the ice water, and make sure the return hose is secure in the bucket.

4. Plug in the pump. Lift the drain hose to confirm that water is flowing. (If it's not, shake the pump gently to prime it.)

5. Plug in the chamber. This activates a Peltier cooler which will chill the chamber floor to -35C[2].

6. Wait 20-30 minutes for the chamber floor to cool to -35 C. You should observe a thick, drizzle-like, condensing fog in the chamber. You may observe random tracks in the chamber.

7. Take the **radioactive source needle**, stored in a cork in a test tube. The lower (longer, narrower) end is the radioactive one. Withdraw the cork from the storage tube and insert it into the hole in the chamber, so the radioactive tip is near the bottom and the cork plugs the hole. You should now see tracks.

8. Using the supplied wire, connect the high-voltage banana plug (on the front of the chamber) with the top of the radioactive source needle. This will help clear the chamber of ions, and reduce the non-track-like fog condensation rate.

Don't break things: Never flip a pump "on" and blindly assume it's working. Verify the fluid is moving.

Safety: Never have the chamber power on without the cooling water flow.

Safety: Do not touch the radioactive end; only touch the cork. The ^{210}Pb is right on the surface, and may transfer. Store the needle in its tube.

3.2 Using compressed gases

Later in the lab you may want to backfill the chamber with a gas other than air. We have CF_4 and Helium. Safe handling of compressed gas is an important technical skill and we want you to learn it. CF_4 and He are nontoxic and non-flammable, but must be treated carefully because they are stored under high pressure. To vent the chamber with any gas, **follow these directions exactly. These standard, safe procedures involve both manipulating the valves safely, and anticipating a safe response if any particular component should fail.**

Safety: Compressed gases are a serious business. Follow instructions very carefully.

1. Remove the radioactive source so the chamber's top hole is open. Gas will escape through this hole.

2. On top of the bottle, set the regulator control dial to zero, i.e. "loosen" it until you feel no resistance. (You may not see any movement in the gauges. That's fine.)

3. OPEN all of the shutoff-valves between the regulator and the chamber. (Why? If the regulator is imperfect, the next step might release a short "pulse" of high-pressure gas. The system must be ready to vent that pulse, not try to contain it.)

4. Think ahead: what if one of the gauges were to "pop"? Where would the glass face go flying? Don't stand in the line of fire.

Safety: The chamber is not a pressure tank. Gas in = gas out.

Don't break things: if the control dial comes off in your hand, ask for help re-seating it. It's easy to damage the (expensive) screw threads.

[2] A Peltier cooler is a solid-state refrigerator. Like any refrigerator, it moves energy from a cold body (the chamber) to a warmer body (the heat sink). Like any refrigerator, it must consume energy in order to do so; the bigger the temperature difference, the more energy must be consumed/wasted per joule of useful refrigeration. Therefore, the device works best when the heat sink temperature is low—thus the use of ice water. Both the consumed-energy and the energy-moved-from-the-cold are being dumped into the heat sink; therefore, the exhaust water is warmer than 0C and will melt the ice while you are working.

5. Open the cylinder valve. The high-pressure gauge should jump, with a clunk, showing the cylinder pressure. The low-pressure gauge should remain at zero. No gas should flow.

6. Turn the regulator control dial, gradually, until you feel it make contact with the spring.

7. Turn it a little further—maybe a few millimeters—while **listening for the hiss**. When you can hear gas flowing, the chamber is flushing.

With that, you've safely *started* the gas flow. The goal is to displace the air from the chamber, then seal it off.

Safety: Do not run gas continuously during measurements; it is an asphyxiant. If an unusually large amount of gas is vented for any reason, open the lab door for a few minutes to ventilate the room.

1. Guesstimate the rate of gas escaping from the chamber. Flush the chamber enough to exchange its entire volume two or three times.

2. To stop the gas flow, do two things more or less simultaneously:
   - **GENTLY** close the shutoff valve at the regulator exit. Pretend it's the cap on a plastic soda bottle. Muscle-power will damage it.
   - hold the source needle almost in place, not quite seated, and prepare to stopper the chamber.

3. Quickly press the source needle's cork in place to seal the chamber.

When you're done using this gas for the day, close the cylinder valve firmly. Turn it until it stops, then nudge it one millimeter further.

Safety: Do not leave the cylinder valve open overnight.

3.3 Video-assisted readout and analysis

The lab computer includes a video camera with which you can take photographs and video of your events. We suggest that you take distance measurements "by hand" by pausing these videos, and referring to the measuring screen on the bottom of the chamber. There is no automated track-analysis software.

4 Experiments with alpha particles

4.1 Basics

- Turn on the cloud chamber. Can you see tracks made by the alpha particles? Can you see any other tracks? Watch the chamber for a few minutes and develop a catalogue of any different phenomena you see. Can you identify the ^{210}Po events specifically? Are there any other events that *look like* the ^{210}Po decays, but don't emanate from the needle? Are there events that look distinctly different from ^{210}Po? Generate a rough estimate of the rate of each event type in your catalogue.

- Go to the gamma-spectroscopy lab and borrow their strongest gamma-ray emitter. Bring the gamma emitter near the outside of the chamber. Does it have any effect? Do the new effects look like anything you had previously catalogued?

- What difference, if any, do you observe with vs. without the high-voltage ion clearing field?

- First by eye, then with the video camera, estimate the average range of a ^{210}Po alpha particle in air. Include (and discuss) your error bar on this estimate.

- Look at the Bethe-Bloch energy loss formula. Many of the terms depend on the properties of the projectile; which ones depend on the properties of the target? Using this conclusion, and the range-in-air you found above, predict the alpha particle's range in the other gases you have available. After making this prediction, fill the chamber with an alternative gas and see if the new range agrees with this prediction.

- The droplet density (droplets per cm) along a track should increase with dE/dx. (It may not be a linear increase!) You have several ways of obtaining different dE/dx values—you can obtain high dE/dx in the Bragg peak at the end of any track, you can obtain higher or lower dE/dx by changing to denser or less-dense gases. Using any or all of these source of variation, can you construct a graph of droplet-density vs. dE/dx ?

- Go online and learn your way around the ASTAR system (a database for calculating stopping power and range) at NIST. Use the alpha particle range data to measure the ^{210}Po decay energy.

4.2 Advanced techniques

Inside the cloud chamber, accessible via the tweezers, are a set of objects you can use to interact with the alphas: thin foils, a collimator, and a C-shaped permanent magnet. Use these objects as best you can to perform some of the following measurements:

- **Collimation** The supplied polonium needle is releasing alphas in random directions. For some experiments, you may want a *collimated* (i.e., all moving in the same direction) beam. You can do this using a *collimator*. Arrange a block or sheet of material, with a small hole in it, in front of the alpha source; it will block the alphas traveling in most directions, but allow a narrowly-directed subset to pass through. This is called "collimation". Think about the benefits and tradeoffs of collimation. How does the hole size and position affect the event rate? The angular spread (emittance) of the beam? Does an arbitrarily-small hole always produce an arbitrarily narrow beam?

- **Stopping power** We have assembled a collection of thin foils, supplied by the local Lebow Company. They are labeled as to material and thickness. (Careful, they're very fragile; handle them only by the frame.) Do alpha particles pass through these foils at all? If so, does passage through the foil affect the particle's subsequent range? Measure such a range, then use the ASTAR database to translate that into "energy after the foil"; use that to measure the energy loss rate in this material. Cross-check the energy loss rates computed from various thicknesses of the same material.

- **"Multiple scattering"** Alpha tracks do not move in perfect straight lines; they waver. This is due to the random statistical nature of Bethe-Bloch energy loss; it's not a perfectly smooth process, it's a series of distinct collisions. Each collision saps a finite amount of energy (on the order of a gas molecule's ionization energy) and perturbs the alpha's momentum in a random direction in 3D. The number of collisions is a random process, and undergoes statistical fluctuations; thus the particle's momentum undergoes a random walk. Non-ionizing "elastic scattering" events will, similarly, perturb the alpha's direction but not its energy, and contribute to this random walk. Photograph a collection of tracks and measure their deviation from straightness. Can you compare these deviations to a multiple-scattering formula?

- **Rutherford scattering** Sometimes, an alpha particle will undergo a *hard* collision—striking one nucleus very hard, and undergoing a large change in momentum. This is what Ernest Rutherford observed when he saw alpha particles bouncing straight back from a thin gold foil. The gold-foil experiment is difficult, but you may see Rutherford scattering from gas molecules. Can you photograph a collection of tracks with sharp kinks in them? What fraction of tracks have such a kink in the first cm of path? Translate this into a *cross section* for Rutherford scattering.

- **Magnetic spectroscopy** OK, here's the fun part. The C-shaped assemblies supplied contain NdFeB magnets in a C-shaped iron yoke. This configuration leads to a very strong, uniform field in the gap, and a very weak field outside the gap. Therefore, the Lorentz force law—$F = qvxB$—is easy to translate into an equation-of-motion. An alpha particle that flies through this gap will undergo a short *arc* of approximately-uniform circular motion with $r = \frac{mv}{qB}$; it will enter the gap going in one direction, and exit going in a different direction.

  The simplest quantity to measure is the *angle of deviation*. Your instructors have measured the magnetic field strength using a Hall probe, and our measurements are written on the magnets. (If you want to recalibrate this, ask for a Hall probe.)

  Do a calculation. What angular deviation do you expect for a 5.5 MeV alpha? Is that plausibly observable?

  What's the lowest-energy alpha that travels far enough to cross one magnet-diameter at all? What deviation do you expect for that one? Attempt to produce such an alpha (I recommend using a helium fill and degrading the alpha energy using foils) and attempt to produce a beam of alphas with appropriately low energy.

- **Velocity / range relationship**

  The magnet gives you a direct method of measuring velocities. Now, rather than using the ASTAR database, you can construct your own range/energy curve. Using various choices of foil, *degrade* the energy of the ^{210}Po alpha beam. Measure the range in gas of such a degraded beam, then introduce the magnet and measure its velocity. This is a datapoint on a range/energy curve; measure several such points, using different degraders, and compare to the NIST ASTAR curve.