Name: ________________________ Partner(s): __________________________

Investigation #14 __________________________

ATOMIC AND NUCLEAR PHYSICS

In this investigation, you will perform a series of short simulations and observations that should provide some insight into the world of atomic and nuclear physics. In particular, you will simulate radioactive decay, measurement of the size of an atomic nucleus, and a nuclear chain reaction. In addition, you will observe the emission spectra of various gases and note how these "atomic fingerprints" can be used to identify elements that compose a substance.

Part I
Radioactivity and Nuclear Half-Life

Some naturally occurring atomic nuclei are unstable and undergo *radioactive decay* into stable nuclei by emitting radiation (either in the form of energetic particles or high energy light).

Background

For a given radioactive material, there is a certain probability that a nucleus will decay. Consider a hypothetical example where you start with 1000 unstable (radioactive) nuclei. Suppose there is a 10% chance a nucleus will decay within a one-hour time span. After one hour, you would expect to find that about 100 of your original atomic nuclei will have decayed, leaving 900 unstable nuclei. If you wait another hour, 10% of the remaining 900 nuclei should decay. That is, 90 more nuclei should decay during the second hour. Thus, after two hours from the start, 190 decays should have taken place, leaving 810 unstable nuclei. After the third hour another 10% (or 81) of the remaining unstable nuclei should decay. This process continues until all the nuclei have decayed.

Note that the number of decays that take place in the given time interval is proportional to the number of unstable nuclei that remain and that this number of remaining nuclei is continuously changing with time.

You will simulate the radioactive decay process by shaking a box containing a large number of dice or pennies (that represent the unstable nuclei) and removing those that come up a certain way (the decay products). For example, if you are shaking a box of pennies, you could remove all the pennies that come up "tails" after a shake and then continue with the remaining pennies until all the pennies have "decayed". Each shake represents a specific time interval.

You will measure the "time" (number of shakes) for a given amount of unstable nuclei to decay to one-half of its original value. This time is called the *half-life* for that material.

Prediction: Suppose you start with 100 pennies. How many shakes do you expect to make in order for 50 of the pennies to "decay"? (Let "tails" represent decays.) Why?

Prediction: Do you think that the number of shakes needed to reduce some original number of pennies to one-half will depend on that original number. Why or why not?

Checkpoint: Consult with your instructor before proceeding. **Instructor's OK:** _______

You group will need to following materials/equipment for this part:

- Box with lid
- 100 pennies or counting chips
- 100 dice

Procedure

1. Start by placing the 100 pennies in the box. Securely fasten the lid. Shake the box vigorously for a couple of seconds.
2. Open the box and remove all the pennies that come up "tails" and put them aside.
3. With the remaining "heads" in box, repeat the shaking process until you either have no pennies left or you have completed all eight rows in the Trial 1 column of Table 1 below.
4. Perform two more trials starting with 100 pennies and then calculate the average number of pennies remaining after each shake. (Fractions or decimal values are OK.)

Table 1

Number of Time Intervals (Shakes)	Number of Unstable Nuclei (Pennies) Remaining			
	Trial 1	Trial 2	Trial 3	Average
0	100	100	100	100
1				
2				
3				
4				
5				
6				
7				
8				

5. Now repeat the previous experiment using the dice. Assume that any die that comes up ‘1’ to have decayed.
6. Complete Table 2 below by performing three trials and taking the average values.

Table 2

Number of Time Intervals (Shakes)	Number of Unstable Nuclei (Dice) Remaining			
	Trail 1	Trial 2	Trial 3	Average
0	100	100	100	100
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				

Questions: Looking at your averaged data column from Table 1, how many "time intervals" (that is, how many shakes) did it take for pennies to decay from 100 to about 50? How many time intervals did it take for pennies to decay from about 50 to about 25? Do your results confirm or refute the predictions you made earlier?

You just estimated the "half-life" of your pennies. Now you will repeat with the dice.

Questions: Looking at your averaged data column from Table 2, about how many time intervals (shakes) does it take to reduce the original amount of dice by half? On average, about how many time intervals does it take to reduce any remaining number by half?

In the **Homework Questions**, you will be asked to plot the average number of nuclei remaining versus the number of time intervals (shakes).

Checkpoint: Consult with your instructor before proceeding. **Instructor's OK:** _______

Part II
Measuring Nuclear Dimensions

In this experiment, you will model the technique used to measure the size of an atomic nucleus. This technique is analogous to the one used by Ernest Rutherford in 1911 when his research group discovered the atomic nucleus.

Background

In the experiment, Rutherford's group aimed "alpha (α)" particles (which were later discovered to be Helium-4 nuclei) from a radioactive source at a thin gold foil to observe the deflection of the α-particles. While most of the beam passed through undeflected, there were occasional "hits" that deflected the α-particles at very high angles—much more than expected based on the model of the atom at that time. Some α-particles were even backscattered at angles close to 180°. Rutherford is said to have described the result "as if you fired a 15-inch shell at a piece of tissue paper, and it came back and hit you."

This result led Rutherford to propose that the positive charge of the atom was not spread uniformly throughout the volume of the atom as originally proposed by J. J. Thomson, but rather, it is concentrated in a very small region (about 10^{-14} m in diameter!) at the center of the atom.

In this simulation, you will use glass beads to represent the atomic nuclei and small metal BBs to represent the α-particles. By repeatedly rolling the BBs randomly toward the beads most will miss but some will hit one or more beads. You can determine the average size of the glass beads by calculating the ratio of hits to the total number of rolls.

Questions: If you were to fire randomly in a 100 cm wide region where a 10 cm object were placed, how many "hits" might you expect to make after 1000 shots? Why? If there were two of the 10 cm objects in the 100 cm region, how many "hits" might you expect to make after 1000 shots (assuming the objects did not overlap)?

Your group will need the following materials/equipment for this part:

- 6-10 glass beads
- 3 metersticks
- Small metal ball bearings (BBs)
- 1 magnet
- 1 piece of cardboard or thin plywood(80 cm x 80 cm)
- 1 caliper

Procedure

1. To measure the size of your nuclei (the glass beads) line up a pair of meter sticks parallel to each other about 60 cm apart. Place the third meter stick along the ends of the other two metersticks as shown in Fig. 1 below.
2. Spread the glass beads more or less randomly between the sticks close to one end of the parallel metersticks. Be sure that they do not overlap along the direction of the rolling BBs.

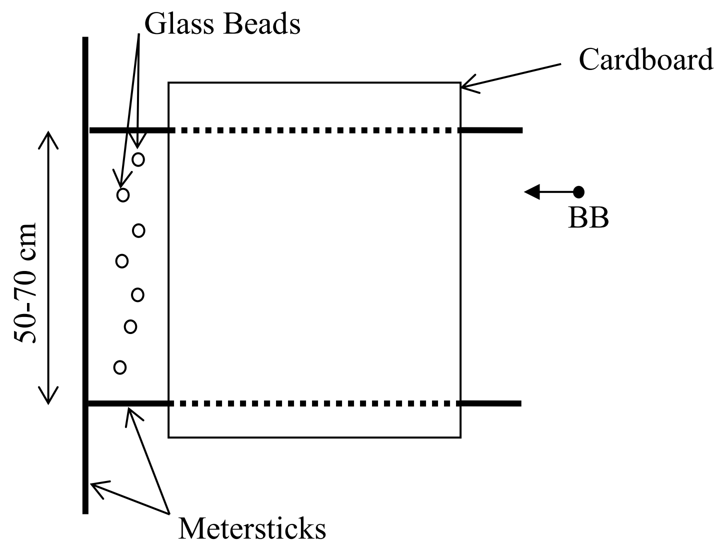


Fig. 1: Set-up for the Rutherford scattering simulation.

3. Have one person roll BBs one at a time at random toward the beads.

Note: It will be very important that you perform the rolls randomly. It will help to cover the meter stick with a board (Fig. 1) so that the person rolling cannot see the glass beads.

4. The other person should then count the trials and the number of direct hits. You will need a large number of valid rolls (about 200) before your results will become statistically significant.
5. Use the following guidelines to count valid rolls and hits:
   a. A "valid roll" is one in which the BB does not strike either side rail before hitting a bead or the back rail.
   b. A "hit" is counted if a BB from a valid roll strikes a bead before hitting any rail.
   c. A BB that hits the back rail first and then bounces back to hit a glass bead counts as a "miss."
   d. A BB that hits two or more beads on a single valid roll only counts as one hit.

Helpful Hint: It will probably be easiest to keep track of rolls and hits if the person rolling the BBs stops after every 20 rolls or so in order to allow for data taking. This will reduce the chances of your losing count. In addition to recording data, stopping will allow you to clear the region of stray BBs that may have rebounded back into the rolling area. You can use the magnet to quickly collect the stray BBs.

Table 3

Valid Rolls	Tally of "Hits"	Tally of "Misses"	Valid Rolls	Tally of "Hits"	Tally of "Misses"
1-20			101-120		
21-40			121-140		
41-60			141-160		
61-80			161-180		
81-100			181-200		
Totals:			Totals:		

6. Check that your total number of "hits" + "misses" adds up to your number of valid rolls (which should be 20) for each section in Table 3.
7. Record your total number of valid rolls and the number of "hits" in Table 4 on the next page.
8. Calculate the probability of a hit by dividing the number of hits by the total number of valid rolls. That is,

$$P_{hit} = \frac{N_{hits}}{N_{rolls}}$$

Table 4	Number of Rolls N_{rolls}	Number of Hits N_{hits}	Probability of Hit N_{hits} / N_{rolls}

The probability of a hit can also be calculated by dividing the available target width by the entire width of the region. That is,

$$P_{hit} = \frac{\text{Total Target Width}}{\text{Total Available Width}} = \frac{N_{target} d_{nucleus}}{L}$$

In the above equation, N_{target} is the number of glass beads, $d_{nucleus}$ is the average diameter of a single glass bead, and L is the separation distance between the side rails that you used. Since both equations above represent the same probability, the size of the glass bead can be determined by equating the two expressions and solving for $d_{nucleus}$. That is,

$$d_{nucleus} = \frac{N_{hits} L}{N_{target} N_{rolls}}.$$

9. From your data calculate the average diameter of your glass beads based on the probability of a hit.

$d_{nucleus}$ = ___________ cm

10. Using the caliper or a centimeter ruler, measure the diameter of four randomly chosen beads. Since the beads are more elliptical rather than perfect circles, measure each bead across the "major axis" and the "minor axis" of the ellipse and calculate the average diameter for each bead. Then calculate the overall average bead diameter. Complete Table 5 below.

Table 5	Smallest Diameter (cm)	Widest Diameter (cm)	Average Diameter (cm)
Bead 1			
Bead 2			
Bead 3			
Bead 4			
		Overall Average Bead Diameter:	

11. Taking the overall average result as the accepted value, $d_{accepted}$, for the diameter of the beads, calculate the percent error of your diameter measurement from the BB's:

$$\% \ Error = \frac{\left| d_{nucleus} - d_{accepted} \right|}{d_{accepted}} \times 100\% = \_\_\_\_\_\_\_\_\_\_ \%$$

Checkpoint: Consult with your instructor before proceeding. **Instructor's OK:** ______

Part III
Nuclear Chain Reaction

This simulation is designed to illustrate the concept of a *chain reaction*. Suppose you told a secret to one person, and that person told a third person, and that third person told a fourth person, and so on. In principle, a *critical* chain reaction has been initiated. This particular chain reaction is classified as "critical" since each "event" triggers only one additional event.

If, on the other hand, you told a secret to two people, and then they each told two people and each of those four people told two people, and so on, you will have set off a *supercritical* chain reaction. This term "supercritical" implies that each event triggers more than one additional event. You will simulate each chain reaction using dominos.

You will need for this part:

- 101 dominoes
- stopwatch

Procedure

1. Set up a length of dominoes each about a half a domino length apart in a line. To simulate the critical chain reaction, the dominoes should be arranged "single-file" as demonstrated in Fig. 2 below. (The line can have any shape, but be careful: if the turns are too sharp, a particular domino may not knock down the one behind it.)
2. The same person should push the first domino start the stopwatch to record the time until the last domino falls.
3. Record the time for all the dominoes to fall for this chain reaction: $T_{101,c}$ = _______ s.

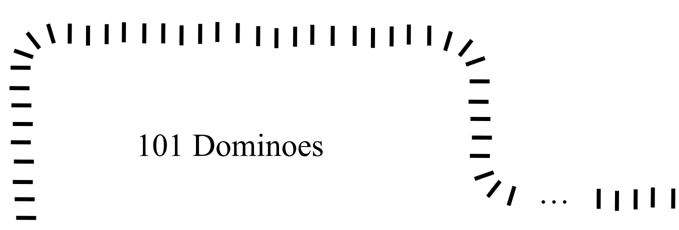


Fig. 2: Example of single file set-up of the dominoes.

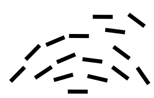
Question: Based on the time it took for 101 dominos to fall, how long does it take for one domino to fall? This is the average time for one domino to "knock" into the next. (Note that there are 100 time intervals between the first and last domino.)

$$\Delta t_{ave} = \frac{T_{101,c}}{100} = \_\_\_\_\_\_\_\_\_\_\_\_ \text{ s}$$

Question: If instead there had been 201 dominoes, how long would it have taken for the critical chain reaction to take place? Show your calculation and/or reasoning.

$T_{201,c}$ = ______ s

4. To simulate the supercritical chain reaction, you need to arrange the 101 dominoes in such a way that the first domino knocks over two dominoes and each of those two knock over two dominoes, and so on. This is illustrated somewhat in Fig. 3 below.



… 101 Dominoes (?)

Fig. 3: Attempted set-up to make one domino hit two, and those two hit four, etc.

Question: What difficulties do you anticipate encountering while trying to set up this type of configuration?

Instead of actually setting up the dominoes in this fashion and trying to time the reaction, you will instead reason through the difficulties in order to get the time for 101 dominoes to fall. Consider "one hits two," "two hits four," etc. as shown in Table 6 below:

<table>
<tr><td>Table 6</td><td>Row 1</td><td>Row 2</td><td>Row 3</td><td>Row 4</td><td>…</td><td>Row n</td></tr>
<tr><td># in row</td><td>|</td><td>|
|</td><td>|
|
|
|</td><td>8</td><td>…</td><td>$2^{(n-1)}$</td></tr>
<tr><td>Total # fallen</td><td>1</td><td>3</td><td>7</td><td>15</td><td>…</td><td>$2^n - 1$</td></tr>
</table>

Question: For this supercritical chain reaction (in which the one domino in the first row knocks over the two in the second row, and those two knock over the four in the third row, and those four knock over the eight in the fourth row, and so on), how many "rows" are needed in order for a total of 101 dominoes to fall? (In other words, in which row would you expect to find the 101st domino?)

$$N_{rows,101} = \_\_\_\_$$

Question: For this supercritical chain reaction, how many time intervals (Δt_{ave}'s) elapse after a total of 101 dominoes fall? (Recall that the number of time intervals is one less than the number of rows.)

$$N_{intervals,101} = \_\_\_\_\_\_\_$$

Question: Based on your measured time interval for one "knock," how long should it take for all 101 dominoes to fall for this supercritical chain reaction?

$$T_{101,sc} = (N_{intervals,101})(\Delta t_{ave}) = \_\_\_\_\_\_\_ \text{ s}$$

Question: If instead there had been 201 dominoes in this supercritical chain reaction, how many "rows" are needed in order for a total of 201 dominoes to fall? (In other words, in which row would you expect to find the 201st domino?)

$$N_{rows,201} = \_\_\_\_$$

Question: For this supercritical chain reaction, how many time intervals (Δt_{ave}'s) elapse after a total of 201 dominoes fall? (Recall that the number of time intervals is one less than the number of rows.)

$$N_{intervals,201} = \_\_\_\_\_\_\_$$

Question: Based on your measured time interval for one "knock," how long should it take for all 201 dominoes to fall for this supercritical chain reaction?

$$T_{201,sc} = (N_{intervals,201})(\Delta t_{ave}) = \_\_\_\_\_\_\_ \text{ s}$$

Question: How many times faster is the supercritical chain reaction (one hits two, two hits four, etc.) compared to the critical chain reaction (one hits one, one hits one, etc.) for the case of 101 dominoes? What about for 201 dominoes? (Show your calculations.)

$$T_{101,sc} = \_\_\_\_\_\_ \text{ s}$$

$$T_{201s,c} = \_\_\_\_\_\_ \text{ s}$$

Checkpoint: Consult with your instructor before proceeding. **Instructor's OK:** _______

Part IV
Atomic Spectra

In this measurement, you will observe and compare the emission spectra of various gases using a simple spectroscope. Using spectral lines of known wavelengths, you will produce a calibration curve that can be used to determine the wavelengths of spectral lines of other materials.

CAUTION: The apparatus that holds the discharge tube is at a high voltage. Do NOT touch electrodes of the apparatus while it is plugged in.

You will the following equipment for this part:

- 1 handheld spectroscope
- 1 incandescent bulb
- 1 fluorescent lamp
- several discharge tubes containing various gases (hydrogen, helium, etc.)
-

Procedure

1. Examine the handheld spectroscope. It consists of a triangular box with a *diffraction grating* at the tapered end. (The diffraction grating acts like a prism and disperses the light that enters the narrow slit in its components colors.) The wide end has a narrow and a numerical scale.
2. Turn on the incandescent lamp and look through the diffraction grating at tapered end of the spectroscope as shown in Figure 4 below. Move the box until the light from the incandescent lamp enters the slit and produces a bright array of colors under the numerical scale. Note the approximate numerical reading for each color.

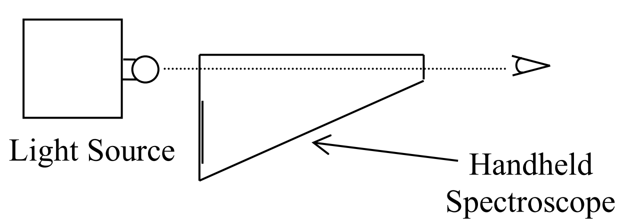


Fig. 4: Overhead view of how to orient the spectroscope.

Question: Describe the spectrum produced by the incandescent lamp.

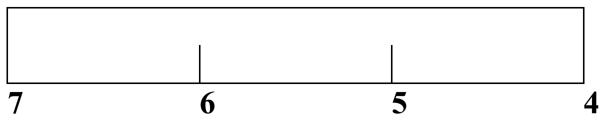
3. Turn on a discharge tube containing He (helium) gas. Hold the spectroscope 1 cm or so from the light source. As before, look through the grating and move the box until the light from the excited helium enters the narrow slit and produces a bright emission

spectrum under the numerical scale. You should see a series of colored lines. You may want to keep the incandescent lamp on and nearby so that you can read the scale. However, do not to let the light from the incandescent lamp overpower the light from the excited helium gas.

4. Note how many lines and colors are clearly visible and record the number and color of the distinct lines that you observe in Table 4 on the next page.

Sketch: Make a simple sketch below showing what you observe along the scale of the spectroscope for the helium spectrum.

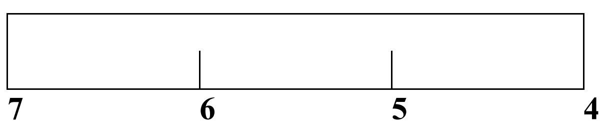
Gas 1: Helium



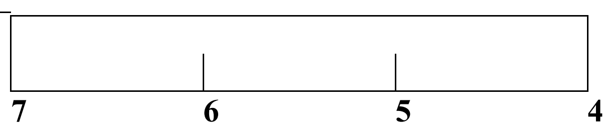
Questions: How many clearly distinct lines in the visible spectrum do you observe for helium? What are the colors of each line?

5. Repeat the above procedure for three additional discharge tubes with different gases one of which is hydrogen. For each of the other discharge tubes, sketch the pattern observed in the spaces below, and record the number and color of the distinct lines that you observe in Table 4.

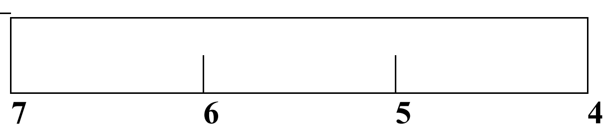
Gas 2: Hydrogen



Gas 3: _____________



Gas 4: _____________



6. Now aim the spectroscope at a fluorescent lamp and observe the resulting spectral distribution. Make note of what you see in the spectroscope.

Table 4

Discharge Gas	Number of Distinct Lines	Colors of Lines
Helium		
Hydrogen		
Gas 3: _____________		
Gas 4: _____________		
Fluorescent Lamp		

Note: The scale of the spectroscope represents wavelengths of visible light in hundreds of nanometers. Visible light wavelengths fall in the range of ~400 nm to ~700 nm. (Recall that 1 nm is 10^{-9} m.) The emission spectrum for each element should be different. While some elements may display similar colors, not all of the distinct lines will appear in the same place on the spectroscope. That is, the lines of different elements will have different wavelengths.

Questions: What color corresponds to the longest wavelength of visible light? What color corresponds to the shortest wavelength?

Checkout: Consult with your instructor before exiting the lab. **Instructor's OK:** ______