Fukushima – Athens: Miss Aimi's jacket

Guiding Theme:
Creativity in Science Education
Three Experiments

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PROLOGUE

In the school year 2013-14 an educational program (http://evgpot.weebly.com/) was held on Environmental Radioactivity during which the three (3) experiments described on this paper were conducted. The true story of Aimi was firstly narrated to us by the Head of the Department of Environmental Radioactivity of the Greek Atomic Energy Commission (GAEC). Miss Aimi travelled from Japan to Athens shortly after the nuclear accident of Fukushima. Ignoring the orders of the Japanese Authorities to the citizens to stay in their homes, Miss Aimi wears her jacket, gets her suitcase and comes out in the rain. On the way to Tokyo Airport, both she and her jacket were exposed to the radionuclides coming from the rain and the air. The GAEC grants us the radioactivity measurements made at its laboratory premises in Athens and this launches the idea for the second experiment. Moreover, the GAEC lends us the radon total alpha-beta counter "Inspector, Radiation Alert", in order to conduct the first experiment. In the third experiment, we study the radioactive decay playing dice. The three experiments cover two themes:

i. Exposure to indoor radioactivity (Experiment 1)
ii. Exposure to radioactivity due to a nuclear accident (Experiments 2A and 2B).

The experiments are:

1. *Measuring radioactivity using a balloon*
2A. *Fukushima – Athens: Miss Aimi's jacket*
2B. *Playing the radioactive decays …on dice*

THEORETICAL CONTEXT

The three experiments were performed in accordance with the principles and the rationale of Inquiry Learning (*Inquiry Based Science Education, IBSE*). The approach is student-centred and includes activities which contribute to decision making in topics related to everyday life (Inquiry-based Science Education in Europe: Reflections from the PROFILES Project, 2012).

From a scientific perspective, Radioactivity is taught as well as the concepts associated with it, such as radioactive decay and half-life.

From a social and educational perspective, students are facilitated in:

- ✓ creating an awareness of the dangers caused by a long exposure to radon and taking precautionary measures
- ✓ creating an awareness of the hazards arising after a nuclear accident as well as familiarity with the plan for dealing with nuclear and radiological emergencies as it is set out by the government and the competent institution, GAEC.

The teaching approach follows the *three stage model* (Inquiry-based Science Education in Europe: Reflections from the PROFILES Project, 2012):

1. Introductory Scenario – For experiment 1, a brochure on radon (http://www.eeae.gr/gr/docs/president/_radonio.pdf) issued by the GAEC for public information is given to students. For Experiments 2A and 2B, students are given the true story of Miss Aimi (http://evgpot.weebly.com/the-true-story-of-aimi.html). Through the brainstorming process students are guided in asking questions and making inquiries as well as emerging alternative ideas. Regarding the experiment 1, the central question is formulated as follows: "*Where can indoor radioactivity be found and how can it be measured?*". As for the experiments 2A and 2B, the central questions are: "*What form has the decay curve N(t), how does it become the statistical character of the radioactive decay and what is the meaning of* *half-life?*". The goal of this stage is to focus the students' interest on the subject as well as to enable them to gain a general knowledge of Radioactivity.

2. Investigation in the Laboratory – Students are asked which of the three experiments they want to do and the class is divided into five groups. Four envelopes for each of the groups are prepared and displayed on teacher's desk, containing gradual guidance that regards the experimental methods, the results and the conclusions.

Our initial laboratory activity was a primary finding of radioactive dust on electrically charged balloon using a Geiger- Müller detector, connected to the Multilog data logger, and the DB-Lab software. In order to conduct the experiment more systematically, we requested the GAEC to help us, so the scientists gave us the radon monitor "Inspector, Radiation Alert".

Regarding the experiment 2, the GAEC radioactivity measurements on Aimi and her jacket were presented to the students. Then students constructed graphs using simulated measurements. Finally, the last experiment was conducted by playing dice. Students compared the findings from experiments 2A and 2B.

The goal of this stage is for students to acquire research skills and through scientific method to learn concepts associated with radioactivity.

Data analysis: Students present data with tables, graphs and draw conclusions. A spokesperson in each group announces the results and conclusions of the group.
The three experiments are described later in this paper.

3. Decision making – Based on the knowledge gained from the experiments, students answered the following questions: *How can we reduce the indoor radon concentration in buildings? What would you advise someone in order to reduce the risk of developing lung cancer due to radon? What remedial action should be taken to reduce radon levels?*
What are the measures taken by the competent national regulatory authority (GAEC) to respond to radiation emergencies?
Students construct a concept map explaining the health effects of nuclear accidents. Through a socio-scientific role play, students conclude whether the risk due to Fukushima accident is associated with airborne radionuclides or with those that enter the food chain.
Reflection on the issue of Radioactivity, based on data obtained from the inquiry.

1. Measuring Radioactivity Using A Balloon

Students are usually more interested in using a radioactive source obtained directly from their environment than using commercial sources (Walkiewicz, 1995). The experiment described here demonstrates the presence of radon gas in houses, schools or other buildings. It also shows that air contains radioactive material at low levels which decays with time (Cowie, et al., 1992, Whitcher, 2011).
The balloon, after charged by friction, picks up radioactive dust particles from the air rendering radioactivity measurable.

The concepts that are studied in this experiment are:

- the radioactive decay
- the half-life

and the physical quantities that are estimated are:

- the "effective half-time" for the overall decay of Pb-214 and Bi-214, both Rn-222 daughters
- the "effective half-time" for the overall decay of Pb-212 and Bi-212, both Rn-220 daughters

- the initial amounts of Pb-212 and Bi-212.

The balloon was placed in a basement where we expect larger amounts of radioactivity compared with a floor. Radon gas, ^{222}Rn, penetrates the ground and several daughter products become attached to positive charged aerosol particles (Soilleux, 1970; Walkiewicz, 1995).

Theory

The radon gas is a by-product of the alpha-decay of ^{226}Ra, which in turn is a by-product of ^{238}U, traces of which are found throughout the crust of the Earth (Cowie, et al., 1992). Radon is a noble gas and diffuses out of the ground at an average emission rate world-wide of the order 1000 atoms/(sec·ft^2) (Cohen, 1979). The a-decay of ^{222}Rn ($t_{1/2}$ = 3.8 days) leaves a charged particle of radioactive ^{218}Po in the air. The two main decay chain of ^{222}Rn and ^{220}Rn of interest of our experiment are shown in Fig.1.

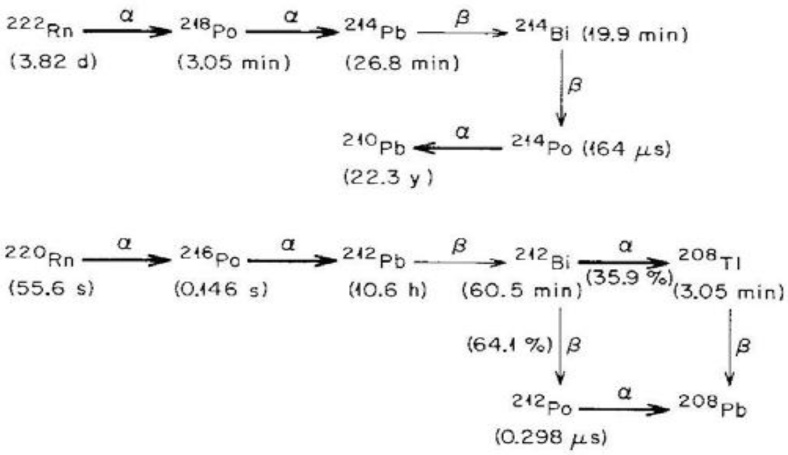

Fig. 1.

Decay schemes of ^{222}Rn and ^{220}Rn

(Papastefanou, 2009).

The radioactive decay curve is mainly due to the decays of Pb-214 and Bi-214 and yields an "effective half-time" of 46.5 min (26.8min+19.7min). There is also a fair amount of radioactivity from Pb-212 (Austen, et al., 1997). We fit the data with the following function:

$$\mathbf{C = A_b \cdot exp(-\lambda_b \cdot t) + A_p \cdot exp(-\lambda_p \cdot t)}$$

where the constants are found by the fit and λ is related to the half-time by the formula: $t_{1/2} = \frac{ln2}{\lambda}$. We use PSI-Plot as it can fit two exponential functions. Moreover, we estimate the (Isaac, et al., 2010):

- initial amount of Pb-212:

$$P_o = \left(\frac{A_P}{\lambda_P}\right)\cdot\left(\frac{\lambda_b - \lambda_p}{2\lambda_b - \lambda_p}\right) \qquad (1)$$

- initial amount of Bi-212:

$$B_o = \left(\frac{A_P}{2\lambda_b - \lambda_p}\right) + \frac{A_b}{\lambda_b} \qquad (2)$$

Experimental Procedure

1. We inflated a balloon (30cm), rubbed it vigorously for about 1min with woolen gloves and we let it suspended in the air. Using the Inspector, Radiation Alert we found the background radioactivity by taking measurements every 10min for 150min. The mean value was:

28 counts/min

2. After 45min the balloon was deflated and placed close to the detector.

3. The measurements for the first 5min indicated a count of:

124.4 counts/min

This increased measurement raised concerns even though we knew that background radon levels in Athens are low.

4. For the ***first 2 hours***, we recorded the decays by taking measurements every 5min and taking into account the background (**Table 1**). Students plotted, (first by hand and then with Excel), *ln*R (the natural logarithm) versus time (**Fig.2**), where R the count rate. From the slope of the straight line, they found the effective half-life.

5. ***After 24 hours***, measurements were carried out every 40min, taking into account the background, this time equal to 25 counts/min (**Table 2**). The overall decay curve (**Fig.3**) is due to the decays of Pb-212 and Bi-212, both Rn-220 daughters.

Data Analysis

➢ FOR THE FIRST 2 HOURS

Table 1: Measurements for the first 2 hours

s/n	t (min)	R (Counts/min)	R (Counts/min) (Net)	*ln*R	s/n	t (min)	R (Counts/min)	R (Counts/min) (Net)	*ln*R
1	0	-	-	-	13	60	95.6	39.6	3.678829
2	5	124.4	68.4	4.225373	14	65	81.6	25.6	3.242592
3	10	120.8	64.8	4.171306	15	70	89.6	33.6	3.514526
4	15	110.8	54.8	4.00369	16	75	72.8	16.8	2.821379
5	20	110.4	54.4	3.996364	17	80	75.6	19.6	2.97553
6	25	121.6	65.6	4.183576	18	85	74.4	18.4	2.912351
7	30	112.8	56.8	4.039536	19	90	76	20	2.995732
8	35	97.2	41.2	3.718438	20	95	67.6	11.6	2.451005
9	40	110.8	54.8	4.00369	21	100	78	22	3.091042
10	45	90.8	34.8	3.549617	22	105	71.6	15.6	2.747271
11	50	88.8	32.8	3.490429	23	110	70.8	14.8	2.694627
12	55	100.8	44.8	3.802208	24	115	69.6	13.6	2.61007

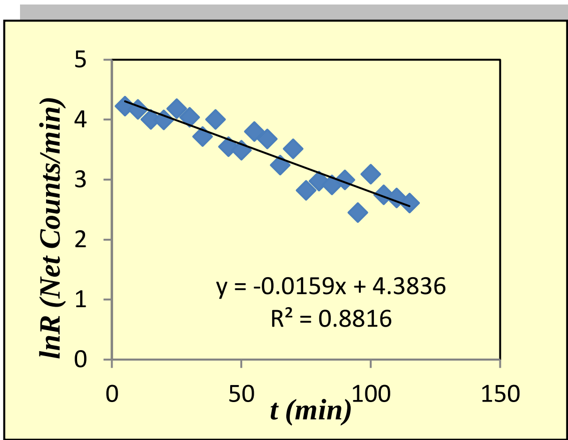

Fig.2: *Decay of the radioactivity on the balloon* *<u>for the first 2 hours</u>* *(background: 28 counts/min).*

This full line is a fit to the data taking into account the two exponentials for Pb-214 and Bi-214. Its slope is equal to λ = 0.0159 min^{-1}. Since $t_{1/2} = \frac{ln2}{\lambda}$, we estimate:

$t_{1/2}$ = 43.59 min (*experimental value*)

The theoretical values of the half-lives of Pb-214 and Bi-214 are:

$t_{1/2\,(p)}$ = 26,8 min for Pb-214

and

$t_{1/2\,(b)}$ = 19,7 min for Bi-214

So, the effective half-time of Pb-214 and Bi-214 is:

$t_{1/2} = t_{1/2\,(p)} + t_{1/2\,(b)}$ = 46.5 min (*theoretical value*)

Namely, the estimated error is 6.3%.

➢ AFTER 24 HOURS

Table 2. Measurements after 24h.

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	t (h)	R (Counts/min)	R_net (Counts/min)	ln(R_net)
1	1.3333	29.9750	4.9750	1.6044
2	2.0000	29.2500	4.2500	1.4469
3	2.6667	28.5750	3.5750	1.2740
4	3.3333	28.2250	3.2250	1.1709
5	4.0000	27.7250	2.7250	1.0025
6	4.6667	27.5250	2.5250	0.9262
7	6.0000	27.5000	2.5000	0.9163
8	8.0000	27.6750	2.6750	0.9839
9	8.6667	27.0250	2.0250	0.7056
10	9.3333	26.9250	1.9250	0.6549
11	10.0000	26.2500	1.2500	0.2231

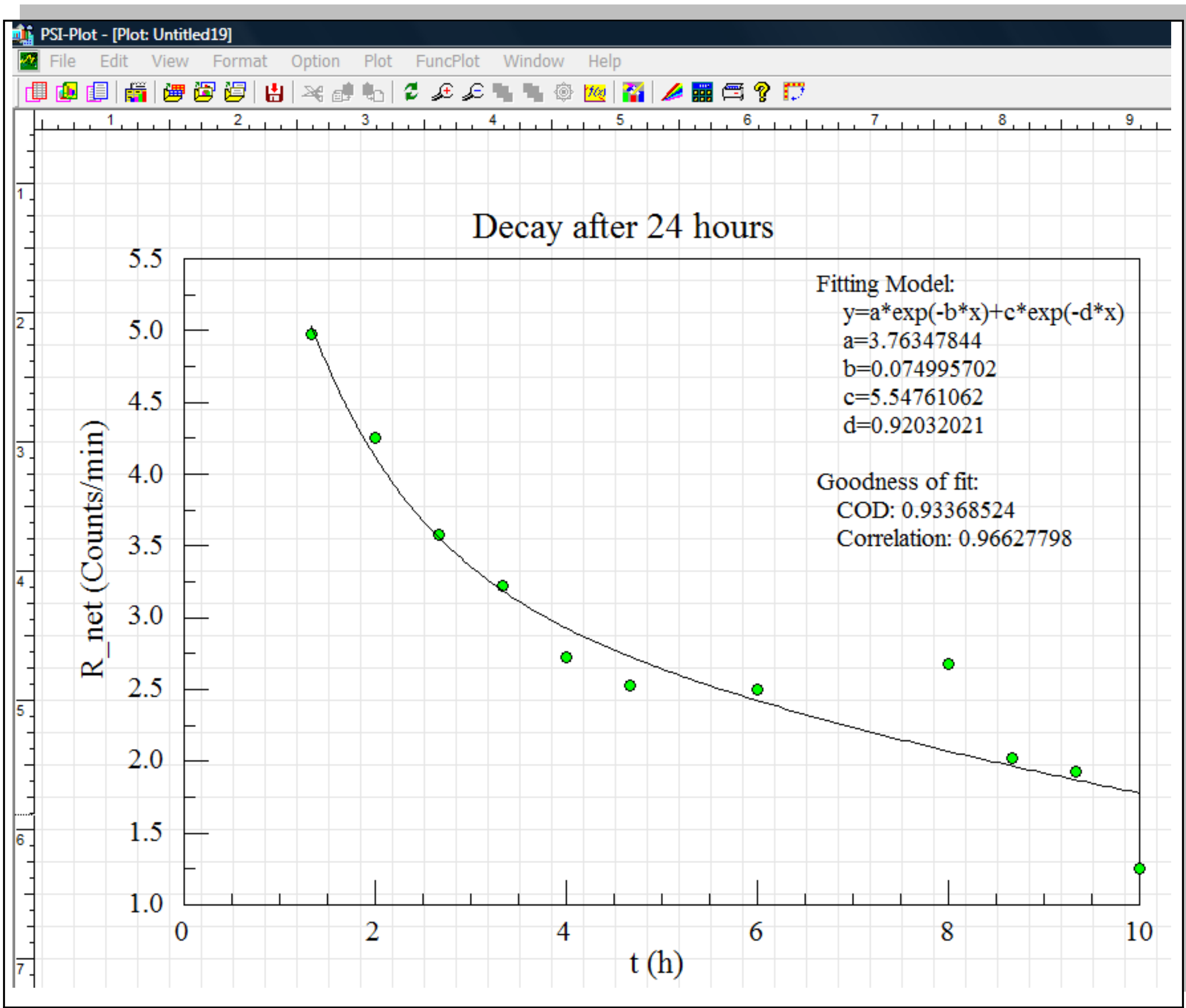

Fig.3: *Decay of the radioactivity on the balloon after 24 hours (background: 25 counts/min).*

From this graph, we find the constants λ_p and λ_b. Using the formula $t_{1/2} = \frac{ln2}{\lambda}$ for each of the nuclei, we find:

$t_{1/2\,(p)}$ = 9.24 h for Pb-212

and

$t_{1/2\,(b)}$ = 0.75 h for Bi-212

So, the effective half-life for the successive decays of Pb-212 and Bi-212 is:

$t_{1/2} = t_{1/2\,(b)} + t_{1/2\,(p)}$ = **10 h** (*experimental value*)

which is satisfactorily to the theoretical value (11.6h).

Using the formulas (1) and (2), we estimate the initial amounts of Pb-212 and Bi-212:

P_o = 6.6 counts/min and B_o = 43 counts/min

where A_p = 5.5 counts/min (constant c of Fig.3) and A_b = 3.76 counts/min (constant a of Fig.3).

Students are asked to explain the shape of the decay based on known radioactive decay schemes. This shape depends on (Whyte, et al., 1962):

- the sample collection time and
- the waiting time before counting begins.

Students appreciate the level of natural radioactive environment in which we live.

2A. FUKUSHIMA – ATHENS: MISS AIMI'S JACKET

Students are given the story of Miss Aimi (http://evgpot.weebly.com/eta-deltaepsilonsigmapiomicroniotanu943deltaalpha-aimi.html). Measurements of radioactivity on Aimi's jacket showed an increase in the activity concentration of Cs-137 and Cs-134. Aimi keeps her jacket in a nylon bag in the basement of her house. Students are given simulated measurements (Table 3 and Table 4) of the activity vs time of these radionuclides.

TABLE 3
Cs-137

α/α	t (έτη)	Ενεργότητα (Bq)
1	0	820.80184
2	4	766.75101
3	8	713.16794
4	12	662.54093
5	16	588.0961
6	20	522.00079
7	24	462.72821
8	28	441.07662
9	32	404.95337
10	36	365.92749
11	40	348.11895
12	44	333.49825
13	48	309.32504
14	52	256.17625
15	56	260.50914
16	60	256.82331
17	64	231.05126
18	68	213.45816
19	72	177.47055
20	76	190.50424
21	80	159.81553
22	84	166.54503
23	88	145.09683
24	92	122.00881
25	96	104.93365
26	100	132.28692

TABLE 4
Cs-134

α/α	t (έτη)	Ενεργότητα (Bq)
1	0	826.1642
2	0.5	678.608871
3	1	586.304069
4	1.5	525.589521
5	2	463.630513
6	2.5	371.653212
7	3	315.254426
8	3.5	263.034668
9	4	221.139177
10	4.5	213.98038
11	5	202.615883
12	5.5	134.350662
13	6	138.755765
14	6.5	105.03373
15	7	102.548619
16	7.5	91.7206566
17	8	78.0821861
18	8.5	81.0189167
19	9	73.3280297
20	9.5	66.3011267
21	10	46.4383881
22	10.5	79.9343468
23	11	29.1857048
24	11.5	68.8377585
25	12	26.8592067
26	12.5	62.7357477

Students are facilitated to:

1. plot firstly by hand and then with Excel the decay curves of Cs-137 and Cs-134.
2. estimate the activity of:
   - Cs-137
   - Cs-134

   after: i) 10 years and ii) 100 years
3. estimate from the graph the half-life of Cs-137 and Cs-134.
4. compare the decay curves and the half-life of Cs-137 and Cs-134, and draw conclusions.

2B. PLAYING THE RADIOACTIVE DECAYS ...ON DICE

Introduction

Using dice highlights the statistical nature of radioactive decay and it makes possible to plot the "decay" curve. It is a convenient way to introduce the concept of half-time as well as to estimate it.

Theory

If a die is thrown, the number "1" has 1 chance in 6 of coming up. In the decay model we assume that each die represents an atomic nucleus and "1" represents a decayed nucleus. If 120 dice were thrown together we would expect 20 of them to turn up with side "1" facing up. We can say that 20 nuclei decayed. These 20 dice are removed and the remaining are thrown again – we would expect about 16 "decays". The process continues until there are only a few dice left.

Experimental Procedure

Students are divided into 4 groups and each group is given 120 dice (N_o=120) in a box (gift box). After each throw, students record the number of dice removed as well as the number remaining. They tabulate the results making a table with two columns: the number of throws and the number of the remaining dice. They plot a graph of the number of the remaining dice (undecayed nuclei) against the number of throws (it represents the time). Finally, results are combined making for a smoother curve.

Data Analysis

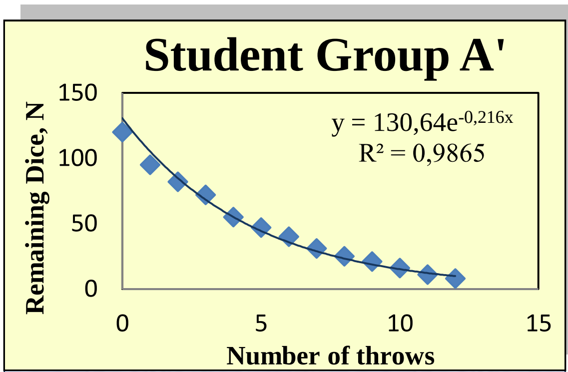

Fig. 4: *The exponential radioactive decay as simulated by throwing dice (Group A').*

Table 5. Dice throws from Group A′

Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N
0	120	**5**	47	**10**	16
1	95	**6**	40	**11**	11
2	82	**7**	31	**12**	8
3	72	**8**	25		
4	55	**9**	21		

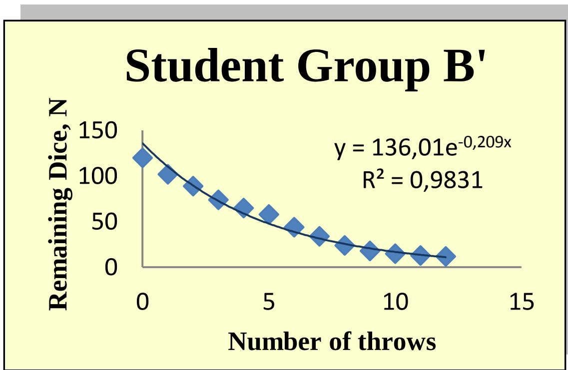

Fig. 5: *The exponential radioactive decay as simulated by throwing dice (Group B').*

Table 6. Dice throws from Group B′

Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N
0	120	**5**	58	**10**	15
1	102	**6**	44	**11**	13
2	89	**7**	34	**12**	12
3	74	**8**	24		
4	65	**9**	18		

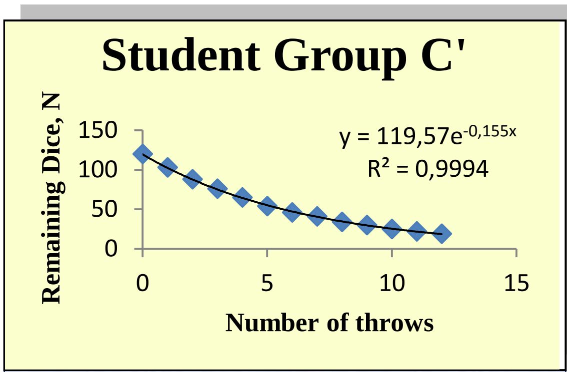

Fig. 6: *The exponential radioactive decay as simulated by throwing dice (Group C').*

Table 7. Dice throws from Group C′

Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N
0	120	**5**	54	**10**	25
1	103	**6**	46	**11**	22
2	88	**7**	41	**12**	19
3	76	**8**	34		
4	65	**9**	30		

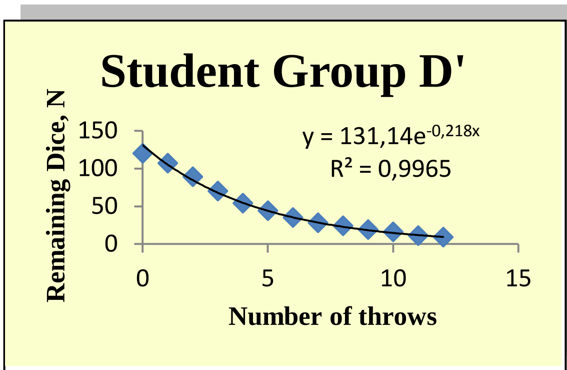

Fig. 7: *The exponential radioactive decay as simulated by throwing dice (Group D').*

Table 8. Dice throws from Group D′

Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N
0	120	**5**	44	**10**	16
1	107	**6**	35	**11**	11
2	89	**7**	28	**12**	9
3	70	**8**	24		
4	54	**9**	19		

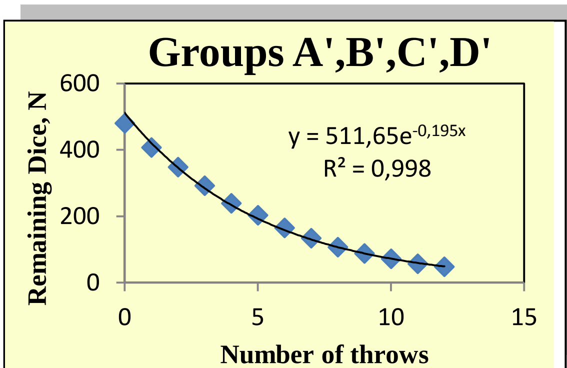

Fig. 8: *The exponential radioactive decay as simulated by throwing dice (Groups A',B',C',D').*

Table 9. Dice throws from Groups A′, B′, C′, D′

Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N	Number of throw	Remaining Dice, N
0	480	**5**	203	**10**	72
1	407	**6**	165	**11**	57
2	348	**7**	134	**12**	48
3	292	**8**	107		
4	239	**9**	88		

Students are facilitated to:

1. recognize the analogy between dice and atomic nucleus as well as between the number of throws and time

2. describe mathematically the shape of the decay curve

3. find the number of throws needed to reduce the number of dice to half of the initial number and then again to the half of the remaining dice, etc

Then, the concept of half-life is introduced. In addition, students are asked to:

4. take into account only the data of student Group A′ (120 dice) and find how many throws are needed to reduce the number of dice to half

5. take into account the data of student Groups A′ and B′ (240 dice) and find how many throws are needed to reduce the number of dice to half

6. take into account the data of student Groups A′, B′ and C′ (360 dice) and find how many throws are needed to reduce the number of dice to half

7. take into account the data of student Groups A′, B′, C′ and D′ (480 dice) and find how many throws are needed to reduce the number of dice to half

8. decide whether the number of throws required to reduce the number of dice to half depends on the initial number of dice

9. explain why the half-life is a more useful concept than the time it takes for all the nuclei to decay

10. compare the decay curve each group plotted and notice whether the four plots are identical. Are there any fluctuations?

11. compare the decay curve of **Fig. 8** with the curve each group plotted and notice which of them is the smoothest

Comparison with the Experiment 2A: "*Fukushima-Athens: Miss Aimi's jacket*"

Students are facilitated to:

12. compare the four plots of Groups A′, B′, C′ and D′ as well as the combination of them with the curves of Cs-137 and Cs-134 derived from the previous experiment.

Conclusions

Radioactive decay is a statistical phenomenon. Each group's curve differs slightly from one to another because the radioactive decay is a random process. Larger number of dice makes for a smoother curve. Radioactive decays can be simulated with a large number of dice. The dice represent the nuclei, the dice with side "1" facing up represent the decayed nuclei and the number of throws represents the time of decay. The time required for half of the dice to decay does not depend on the number of the dice thrown. Comparing the results of Experiments 2A and 2B we conclude that radioactive nuclei have a certain probability to decay in a given time.

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