Radioactive World: An Outreach Activity for Nuclear Chemistry

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ABSTRACT

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Nuclear chemistry is a topic of great societal importance with applications in the realms of medicine, energy, and national security. Despite its significance, this area receives little attention in both K–12 and undergraduate education. This poor coverage arises in part from the lack of suitable educational resources to illustrate key concepts of nuclear chemistry. Here, we describe the development of two activities for the K–12 classroom, which are designed to assist instructors in communicating several conceptual aspects of nuclear chemistry. The first of these activities is an interactive game, called Isotope Rummy, which has been developed as a Lending Library kit through the Cornell Center for Materials Research (CCMR). This game informs students on the composition of the nucleus and factors that determine nuclear stability with respect to radioactive decay. The second activity, called Radiative versus Radioactive Decay, is designed for instructor-led outreach workshops or demonstrations. This activity gives examples of spontaneous radioactive and stimulated photoluminescent decay. We have performed the activities separately and together in various high school classrooms and as a full workshop at a student conference. Feedback obtained from both teachers and students indicates that these activities are helpful for fostering an understanding of several key concepts in nuclear chemistry.

GRAPHICAL ABSTRACT

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KEYWORDS

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High School / Introductory Chemistry; Demonstrations; Interdisciplinary / Multidisciplinary; Public Understanding / Outreach; Collaborative / Cooperative Learning; Hands-On Learning / Manipulatives; Humor / Puzzles / Games; Inquiry-based / Discovery Learning; Isotopes; Nuclear / Radiochemistry.

INTRODUCTION

The lack of availability and access to scientific equipment in low-income neighborhoods greatly contributes to the poor understanding of scientific concepts in school districts within these areas. 1-3 There is increasing concern on the disparities in scientific achievement between students from families with low socioeconomic status versus those from higher class families. In an attempt to counter the socioeconomic gaps in learning, the Cornell Center for Materials Research (CCMR) Educational

Programs Office provides educational resources, called the "Lending Library of Experiments," for schools throughout the country. This Lending Library provides lesson plans and student activities designed to meet the Next Generation Science Standards (NGSS)^{4,5} and are hands-on, inquiry-based, and vary from experiments to interactive games. In this report, we describe a Lending Library kit designed to aid in lessons regarding nuclear chemistry and radioisotopes.

Nuclear chemistry is a particular subject in science that students often struggle to comprehend. 6-8 Poor student understanding and interest in this topic are further exacerbated by the fact that the United States is currently facing a shortage in the nuclear and radiochemistry workforce,9-12 which is responsible for shepherding our nation's nuclear security, energy, and medicine resources.¹³ Therefore, improving student understanding and interest in this subject at the K-12 level may have important implications for maintaining the technical strength of the United States. Naturally, K-12 education in this area presents a number of unusual challenges. In contrast to other topics, such as chemical reactions, the large number of misconceptions and abstract nature of radiochemistry makes it difficult to teach without a physical model. Additionally, the safety concerns associated with radioactive materials, especially for use in classrooms, contribute to the lack of available resources. Two strategies to circumvent the issues regarding limitations in resources and safety hazards are to develop representative physical models and to use household or commercially available items. Activities with these items can act as tangible methods for understanding nuclear chemistry. Among the most effective methods for learning are didactic games in which students practice science with tangible items. Incorporating difficult topics with games help build students' mental structures, increase positive attitudes towards science, and experience peer learning in a fun and interesting way. 14-18 The application of games often leads to reduced tension and stress for students, encourages them to engage in activities, and facilitates the learning process. Here, we describe the two activities, Isotope Rummy and Radiative versus Radioactive Decay, as either Lending Library kits for in-class lessons or as a full workshop for outreach programs.

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Concept and Educational Objectives

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The two activities described in this report cover the NGSS, HS-PS1-8,^{4,5} which requires high school curriculums to include nuclear composition, fission, fusion, and radioactive decay. The activities described can be taught separately or together as a full workshop. We have demonstrated the capability and flexibility of implementing the activities in both settings, namely in high schools and at Expanding Your Horizons (EYH) at Cornell University, a one-day conference for middle and high school girls designed to stimulate interest in STEM fields through hands-on activities. We will discuss the implementation of one activity as a Lending Library kit and also the combination of both activities in a full workshop.

The in-class student activity, Isotope Rummy, is a board game first developed at Cornell University by Professor Hening Lin in 2007. In this report, we have significantly modified this game to incorporate more learning objectives and increase competitive attitudes among students. The activity provides physical models for distinguishing isotopes from one another and aids in abstract thinking. The game board is a modified version of the periodic table, and game cards represent different isotopes, wild, or stable cards to make the activity more engaging and thought-provoking. The objectives of Isotope Rummy are to help students learn about what isotopes are and how they are used in both science and everyday life.

Another workshop activity we developed, Radiative versus Radioactive Decay, aims to teach students about the differences between radiative (photoluminescent) and radioactive decays. This workshop is meant to serve as an outreach activity as opposed to Isotope Rummy, which can be used for both in-class and outreach applications. In the Radiative versus Radioactive Decay activity, students learn about photoluminescence, which includes both fluorescence and phosphorescence, and how this process requires energy to be put into the system in order to get energy out in the form of light. As a second part to this lesson, students learn about the forms of radioactive decay and how this process does not require input energy but instead spontaneously releases energy in the form of particles and electromagnetic radiation. Due to the minor safety concerns, this activity remains as an outreach workshop as opposed to an in-class activity, but we are currently working with

Environmental Health and Safety (EH&S) at Cornell University to make Radiative versus Radioactive Decay a classroom activity.

Safety Hazards

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The Isotope Rummy is a board game, and there are no safety hazards involving this activity. However, the Radiative versus Radioactive Decay workshop activity has minor safety concerns. Photoluminescent materials, comprising non-toxic europium-based powder (alkaline earth metal aluminate oxide doped with europium), are well contained and nonhazardous. However, laser pointers can damage eyes upon direct exposure. To reduce this risk, laser safety glasses should be worn during the photoluminescence exploration activity. Exposure to spontaneous decay from radioactive sources used for demonstration in this activity is relatively low. For example, the activities of the radioactive objects used in Radiative versus Radioactive Decay are exempt from Nuclear Regulatory Commission regulation, and, therefore, do not require special permits for possession and provide no dosimetric concerns to users. These low levels of activity engender no significant exposure concerns for outreach. However, the handling of these radioactive materials should generally be limited to a course instructor. Students will learn about factors that can minimize radioactive exposure from radioactive sources, such as distance, shielding, and exposure time.

DESCRIPTION OF ISOTOPE RUMMY

A complete list of materials and instructions for Isotope Rummy are shown in Table S1 and Figures S1 and S2, Supporting Information (**SI**).

Design of the Cards

There are three different sets of cards in Isotope Rummy including isotope cards, wild cards, and stable cards (Figure 1). Isotope cards (representative card shown in Figure 1a) are separated by element and mass number. The wild cards and stable cards both have actions associated with them (Figures 1b and 1c). The wild cards also contain real-world applications and facts about the corresponding isotope. The different isotope cards are worth varying amounts of points, and the suggested scoring is shown in Table S2 (SI).

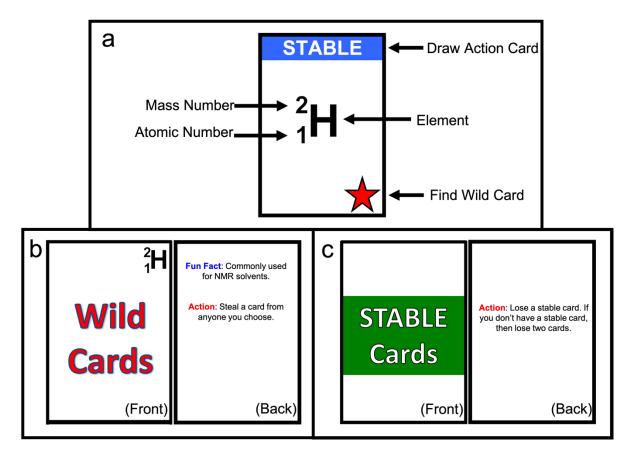


Figure 1. Three different sets of cards included in the Isotope Rummy game are (a) isotope cards, (b) wild card (front and back sides), and (c) stable cards (front and back sides).

Design of the Cards

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The game board is a modified version of the periodic table, which was truncated for manageability and simplification of the activity (Figure 2). There are three major components to the board including placement locations of the isotope cards, wild cards, and stable cards (Figure S1, **SI**). Additionally, the game board indicates that clear marbles represent protons and blue marbles represent neutrons.



Figure 2. The Isotope Rummy game board.

Design of the Game

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The game rules and detailed instructions are described in the tutorials and Figure S2 (SI). The objective of Isotope Rummy is to be the first person or team to earn 100 points by obtaining isotope cards (scoring is shown in Table S2, SI). The point system is designed such that a greater amount of points will be awarded for obtaining a stable isotope card. In each turn, students will begin by rolling the dice; the numbers obtained from the dice roll will signify the amount of "protons" or "neutrons" (clear or blue marbles, respectively) that can be added or subtracted from the "atomic bowl," which

contains an existing quantity of neutrons and protons that represent the isotope currently in play. Based on the dice roll, the student has the choice to add or remove protons and neutrons. Upon carrying out this operation, a new isotope is generated, and the student will take the corresponding isotope card and perform any relevant actions. Based on a given dice roll, students will strategize the addition or subtraction of protons or neutrons to arrive at stable isotopes that award the most points. One suggestion that teachers may provide is to make the ratio of protons to neutrons close to 1 because many stable isotopes have this feature. By the end of the game, students should have a better understanding of what isotopes are, how the number and ratio of protons and neutrons can affect nuclear stability, and how isotopes are used. This activity is designed to last 20–40 min.

DESCRIPTION OF RADIATIVE VERSUS RADIOACTIVE DECAY

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The Radiative versus Radioactive Decay activity has only been performed in a workshop outreach environment and has not yet been developed as a Lending Library kit. However, they can be used as a teacher demonstration. A complete list of materials for this activity is shown in Table S3 (SI). The materials and instructions for assembling "europium shakers," described below, are shown in Figures S3 and S4 (SI). To begin the activity, all students should have the corresponding "Activity Sheets" (SI).

Design of Radiative (Photoluminescent) Decay Activity

The materials for the first half of this activity are for luminescent decay exploration and include the europium shakers. These devices comprise two thin plates of glass sealed to contain non-toxic, phosphorescent europium-doped alkaline earth aluminate oxide powder (Figure 3a). The goal of this activity is to teach students about radiative decay by exciting the powder with blue light (Figure 3b). Upon excitation, the students will observe bright green photoluminescence and understand that energy must be put into the system in order to get energy out. Even after multiple instances of excitation, the europium powder can be mixed and excited again (Figures 3c–3f). This activity is designed to last 10–20 minutes.

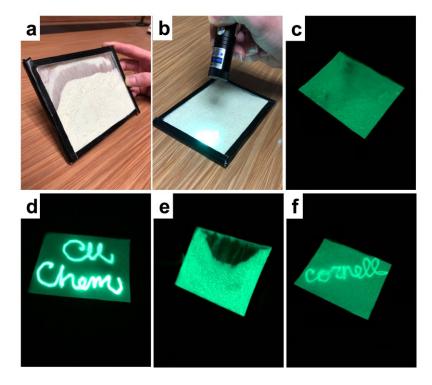


Figure 3. (a) Europium shakers contain photoluminescent europium-doped alkaline earth metal aluminate oxide. The powder can be excited upon (b) application of blue light and (c) shaken to mix the solid solution to erase the imprinted image. The powder can be continuously excited and mixed for multiple rounds (d-f).

Design of Radioactive Decay Activity

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Students will learn about radioactive decay using Geiger counters, shielding equipment, and various radioactive sources (Figure 4, Table S3, **SI**). Several of these sources are chosen to show that radioactivity may be present in everyday objects. Specifically, the use of smoke detectors, as a source of ²⁴¹Am, camping lantern mantles, as a source of ²²⁸Th, and bright orange Fiestaware, as a source of ²³⁸U, clearly illustrates this point. An objective of analyzing these items is to show that we may be exposed to small levels of unharmful radioactivity every day, and that the application of radioactivity, particularly in the case of smoke detectors, can be useful. During the lesson, the teacher will demonstrate how to use the Geiger counter following the tutorial (**SI**) and how to shield from different types of radioactive decay using paper, plastic, or lead. Teachers will show that alpha-emitting sources are blocked by paper, whereas highly penetrating gamma-emitters require layers of thick lead

shielding to be completely blocked. Instructors should note that the majority of alpha and beta emissions are accompanied by gamma rays, and, therefore, the shielding may not completely block the emission from some sources. However, there should still be a clear, observable decrease in counts per minute (cpm) upon shielding. The teacher will emphasize that we are exposed to low levels of radioactivity every day and highlight how some sources are used in everyday objects such as smoke detectors. Lastly, instructors should discuss that radioactivity can be used for beneficial applications, like nuclear energy and medicine, and how limiting exposure time greatly reduces the risk involved in working with hazardous radioactive materials. This activity is designed to last about 20–30 minutes. The instructor can connect this activity to Isotope Rummy by pointing out that radioactive decay is the process by which unstable nuclei change their proton and neutron numbers to become a stable isotope.



Figure 4. Representative materials for radioactive decay activity: (1) paper shield, (2) lead shield, (3) plastic shield, (4) Geiger counter, (5) uranium ore, (6) thorium lantern mantle, (7) ionization smoke detector, and (8) Fiestaware plate.

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RESULTS AND DISCUSSION

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Isotope Rummy Student and Teacher Feedback

Isotope Rummy was performed in different schools located in rural, urban, and city areas. In order to assess the success of Isotope Rummy, we pooled feedback from students, teachers, and parents that participated in these activities. We generated pre- and post-student surveys to gauge if the activity was enjoyable and helpful in understanding isotopes (Figure 5). All feedback is listed in Table S4 (SI). Based on our results, most students were already familiar with the concept of isotopes; this activity, however, mainly served to support or to strengthen the majority (62%) of students' previous knowledge about isotopes. In addition, 80% of the students enjoyed this activity. Many of the students commented about how they "loved the game!" In addition, several students provided insightful suggestions, such as adding "fun pictures" to the cards. This modification would be valuable to implement for the cards that contain "fun facts" to further solidify their grasp on the applications of isotopes. Even though many of the students were familiar with isotopes, Isotope Rummy provides an easy and fun way to reinforce the students' previous understanding, helping them recall and implement this knowledge in the future.

High school teachers were also surveyed during the Cornell STEM Teacher Workshop, which was held in conjunction with the NY Master Teacher Program, at Cornell University. The teachers were allowed to play Isotope Rummy over the course of 30 min as if they were the students doing the activity. We then surveyed the teachers to see how easy Isotope Rummy would be to implement in their classrooms and how useful they thought it would be for engaging and helping the students understand this difficult concept (Figure 6, Table S5, SI). The majority of the teachers (73%) felt that the game would be easy to implement in their classroom, and 91% of the teachers believe that this activity will help the students gain a better understanding of isotopes and their applications. In addition, the teachers thought that Isotope Rummy would be particularly effective for improving the students' critical thinking skills. The teachers also had comments and suggestions that they could implement themselves in their classrooms or ways that we could improve the game to facilitate learning. One suggestion was to laminate the cards to make them easier to handle and to also limit the

amount of time each student has per turn, encouraging students to "think on their feet." Overall, the teachers thought Isotope Rummy was a good model for understanding isotopes and nuclear stability.

Based on the feedback from the students and teachers, we believe that Isotope Rummy provides a good model for conceptualizing isotopes and illustrating nuclear stability. We also gained insight on how to improve the game, such as adding pictures to the cards, and how to make Isotope Rummy more thought-provoking for the students who already have a good understanding of isotopes. The design of Isotope Rummy as a board game provides a fun and interactive learning activity for the students and an easy to implement activity for teachers. These aspects provide a valuable tool for students to understand difficult concepts and how these concepts are applied to real-life scenarios.

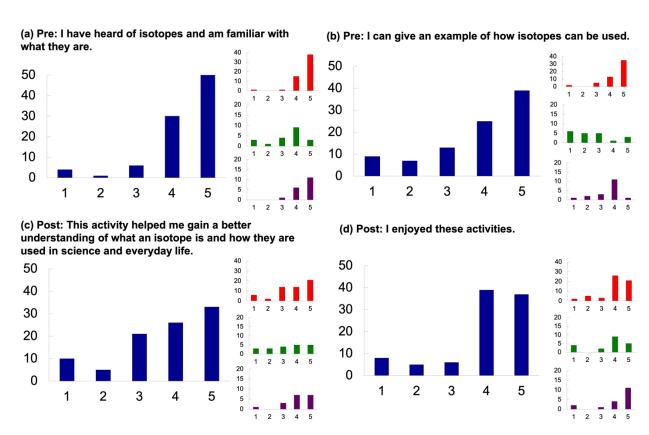


Figure 5. Student survey questions with accompanying histograms of responses where 1 indicates strongly disagree and 5 indicates strongly agree (a–d). Overall response (blue, $n = 93^a$, 95^b), School 1 response (red, $n = 55^a$, 57^b), School 2 response (green, n = 20), and School 3 response (purple, n = 18), where n is the number of students participating in the a = pre-survey and b = post-survey.

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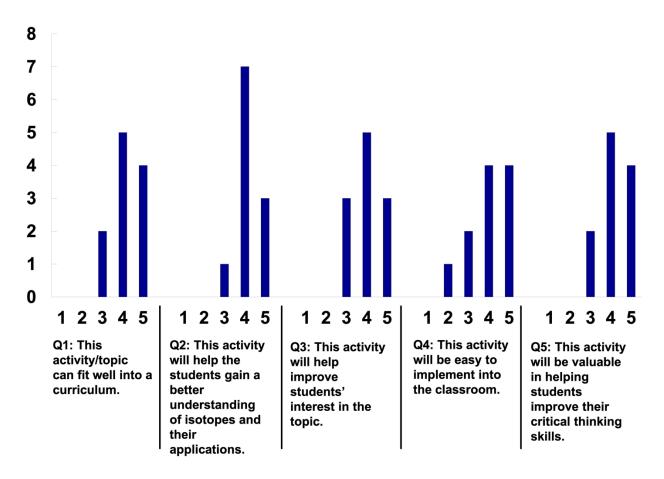


Figure 6. Teacher survey responses where 1 indicates strongly disagree and 5 indicates strongly agree (n = 11).

Full Workshop Student and Parent Feedback

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We have carried out the full workshop, comprising both Isotope Rummy and the Radiative versus Radioactive Decay activity, at the annual EYH conference at Cornell. As described above, the EYH conference invites female middle and high school students to participate in a number of STEM-related activities. The goal of this conference is to inspire these students to pursue STEM fields. During this conference, the students are accompanied and assisted by their parents or a "buddy" (a Cornell student), who also participate in the activities. After completing the workshop, feedback from students, parents, and buddies were obtained in the form of pre- and post-workshop surveys (Figure 7 and Table S6, **SI**).

Based on the feedback from the students and parents, 76% of participants agreed or strongly agreed with the statement, "I enjoyed this activity." Prior to the workshop, only 31% of students had a good understanding of isotopes and 45% of the students had good background knowledge on isotope stability. After completing the activities, 86% agreed or strongly agreed that they gained familiarity with key terms in nuclear chemistry. These results indicate that the workshop was effective in improving students' knowledge and interest in isotopes and radioactivity. We obtained a number of very positive comments stating, for example, the activity "was perfect," "very interactive," or "really informative in a fun way." Another set of comments requested more time to play Isotope Rummy to help them better understand the concepts of stable isotopes. Additionally, participants requested more explanation for both Isotope Rummy and the Radiative versus Radioactive Decay activity. Taken together, these survey results indicate that additional time will allow students to better understand the material and enjoy the activities even more. Implementing this workshop as separate activities in the classroom can help with the time constraint typically involved in combining Isotope Rummy with the Radiative versus Radioactive Decay activity and, therefore, improve the student's understanding of the material.

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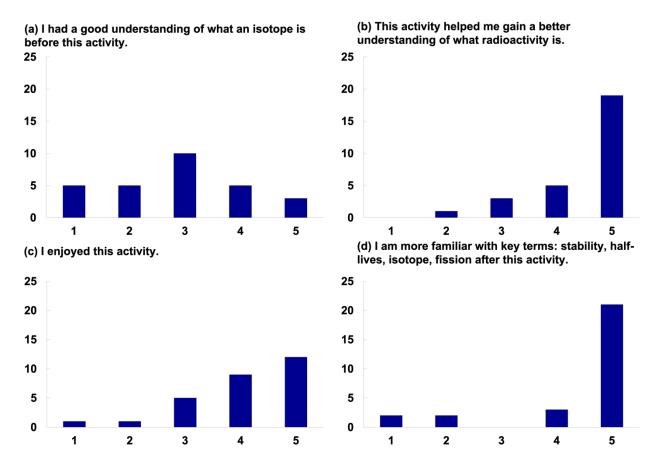


Figure 7. Participant survey questions from EYH conference (n = 28) with accompanying histograms of select responses where 1 indicates strongly disagree and 5 indicates strongly agree (a–d).

CONCLUSIONS

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We have developed the game, Isotope Rummy, which is accessible to all schools across the country, and also the Radiative versus Radioactive Decay activity, which is currently performed as a demonstration or in a full workshop with Isotope Rummy. Isotope Rummy was found to be an effective tool for helping high school students understand the basic concepts and importance of nuclear chemistry. By creating an interactive board game that is accessible to schools all around the country, students are able to engage in learning abstract concepts using tangible materials. The Radiative versus Radioactive Decay activity was also effective for increasing student understanding of nuclear chemistry. Based on the efficacy and interest in the Radiative versus Radioactive Decay demonstration, we are currently pursuing efforts to develop this activity as a Lending Library kit that can be disseminated to high school classrooms across the country. We have received a large amount of

feedback that supports both the need and efficacy of the Isotope Rummy kit and the Radiative versus

Radioactive Decay demonstration. Both of these activities facilitate the learning and understanding of

nuclear chemistry and foster the students' interest in this topic. Given the ongoing need for nuclear

and radiochemists in the U.S. workforce, we hope that these activities can also inspire several of these

students to pursue these careers.

ASSOCIATED CONTENT

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Access to the CCMR Lending Library kits can be found through this link:

http://www.ccmr.cornell.edu/education/educational-resources/lending-library-of-experiments/

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI:

The Isotope Rummy game board, cards, cheat sheet, activity sheet, status-tracking sheet, game rules,

and lesson plan are included in the supplementary materials. The Radiative versus Radioactive Decay

demonstration's cheat sheet and activity sheet are included in the supplementary materials. A

description of how to play Isotope Rummy as well as the Geiger counter tutorial are included in the

supplementary materials.

ASSOCIATED CONTENT

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