Radioactive Consumer Products in the Classroom

By Jack G. Couch and Kelly L. Vaughn

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Dr. Couch and Kelly Vaughn are pictured on the cover.

Most physics teachers are well aware of the fact that orange-colored Fiestaware™ dishes, gas-lantern mantles, and certain other consumer products provide easily measured quantities of radiation. Not as widely known are details about these products and the radionuclides they contain. In this paper we provide product information and data that will be helpful to instructors of introductory physics and physical science in explaining radioactivity demonstrations and experiments to students. Our discussion of potential radiation safety hazards of these products should be of particular interest.

Radioactive Consumer Products

Radioactive Dishes

Brightly colored Fiestaware was first introduced by the Homer Laughlin China Company (HLC) of Newell, West Virginia in 1936. Dishes were originally available in five colors including the popular brilliant orange-red known as "Fiesta red." Various dish styles were offered in the uranium-bearing Fiesta red until midway through World War II when the government assumed control of uranium oxide and the color was dropped temporarily. According to the company, "Fiesta red went to war." Fiesta red returned to the marketplace in 1959 when the Atomic Energy Commission licensed HLC to again buy uranium—this time depleted. The manufacturer explains:

> *Before 1943 the colorant, 14% by weight of the glaze covering the ware [was] uranium oxide U_3O_8 with the uranium content being made up of about 0.7% U-235 and the remainder U-238...the colorant now used is depleted technical grade U_3O_8 with the uranium content being made up of about 0.2% U-235 and the remainder U-238.*[1]

HLC eliminated the color in 1972 and dropped the Fiestaware line in 1973. (Fiestaware was reintroduced in 1986 on the occasion of its fiftieth anniversary, but the favorite Fiesta red was not restored.)

Radioactive Lantern Mantles

The modern gas-lantern mantle had its origin with Carl Auer Von Welsbach, who was first to obtain a patent in 1885. In his early work, the Austrian scientist studied the incandescence of various combinations of oxides containing thorium, yttrium, lanthanum, zirconium, and cerium saturated in a loosely woven fabric hood and exposed to a Bunsen burner. During initial heating of these hoods, called mantles, the fabric is consumed leaving a supporting skeleton of incombustible oxides. The fragile skeleton becomes highly luminous, glowing white-hot in air at high temperatures.[2,3] Worldwide, nearly all versions of the incandescent mantles used in lanterns have thorium as the primary ingredient. Of the thirteen isotopes of thorium, all of them radioactive, the naturally occurring primordial radioisotope ^{232}Th is the most abundant.[4]

The Coleman Company, a major U.S. supplier of gas-lantern mantles, recently discontinued their "green top" thorium mantles and began marketing a Gold Top™ mantle. The new mantle contains (non-radioactive) yttrium instead of thorium.[3] Thorium mantles can still be purchased, however, under other brand names in outdoor camping departments of some large U.S. store chains, including Sears[5] and Target.[6]

It is interesting that radionuclides of all three primordial radioactive series[7] present in the Earth's crust are found in either the orange dish or the thorium mantle. They are the uranium series (^{238}U, 4.468 billion y) and actinium series (^{235}U, 0.7038 billion y) found in the dish glaze, and the thorium series (^{232}Th, 14.05 billion y) found in the lantern mantle. (The long-lived parent and its half-life are listed in parentheses for each series.) These natural series have the following attributes in common: (1) the parent nuclide is long lived, (2) each contains alpha, beta, and gamma emitters, many with short half-lives, (3) each contains an isotope of radon, and (4) each ends with a stable isotope of lead. The isotope ^{222}Rn in the uranium series, together with its daughters, is the main contributor to radon radiation dose.[8,9]

Radioactive Salt Substitutes

Sodium-free salt substitutes such as NoSalt®[10] contain a significant amount of potassium. Natural potassium contains the primordial isotope ^{40}K, which has a half-life of 1.277 billion y. Of the approximately 140 g of potassium in a 70-kg adult, there are 0.016 g, or 4.4 kBq (0.12 μCi), of ^{40}K. This results in an annual radiation dose to the human body from internal ^{40}K of about 190 μSv (19 mrem), mostly from beta particles.[7]

The three primordial radioactive series present in the Earth's crust, together with ^{40}K, are among the most significant sources of natural radioactivity in the Earth and environment. The dish, gas mantle, and salt substitute offer readily available supplies of these natural sources for study in the physics classroom and laboratory. A list of other radioactive consumer products and their exposure levels can be found in References 11 and 12.

Classroom Demonstrations

In our introductory courses, we demonstrate with a Geiger-Müller (GM) detector the presence of radioactivity in a dish, a lantern mantle, and a container of salt substitute. We do this either audibly (with a hand-held GM detector with pancake probe and loudspeaker) or visually (with a GM counter display of counts registered during a one-minute interval). We often measure the gamma spectrum of one or more of the radioactive products as part of our demonstrations. We find that students are very interested in seeing how a spectrum "fingerprint" can identify the radionuclides that are present. For small classes, the spectrum is displayed on a computer monitor at the front of the classroom. For large classes, projection of the spectrum on a lecture-hall screen is possible.

Other products we use in our radioactivity demonstrations include an exit sign containing tritium and a household smoke alarm. Because the beta radiation from the tritium sign and the alpha radiation from the smoke alarm cannot be measured directly, we simply display and describe them to students. Tritium signs typically contain several hundred GBq (several Ci) of tritium (^{3}H) gas, up to the legal maximum of 370 GBq (10 Ci). Tritium emits low-energy beta particles during decay that cannot penetrate the container. The radioactive source inside a typical smoke detector is 37 kBq (1 μCi) of ^{241}Am, which is an alpha emitter. Gamma rays are also emitted, but are difficult to measure because of low source activity. For important safety reasons we deem it inadvisable to expose or remove the radioactive alpha source from the smoke detector. Alpha-emitting radionuclides can be especially harmful if ingested.

Gamma-Ray Spectroscopy

Gamma-ray spectroscopy involves measuring and analyzing the gamma-ray energies usually associated with de-excitation of newly formed nuclei immediately following nuclear decay. Measurements of gamma-ray energies often allow unambiguous identification of parent nuclei, assuming the decay scheme and relevant gamma energies[7,13,14] are already known.

Our spectroscopy demonstration apparatus consists of a 7.6- by 7.6-cm (3- by 3-in) thallium-activated sodium iodide NaI(Tl) detector and associated electronics. Pulses are analyzed for energy by a multichannel analyzer card installed in a personal computer. When set up as a classroom demonstration, the detection system is placed on a lab cart for portability. We shield the detector with lead bricks to reduce background radiation. Details of gamma-ray spectroscopy systems and examples of experiments have been published.[14,15]

We have found that within five minutes of counting time we can collect spectra that are suitable for classroom display. This is true for the dish, mantle, or salt substitute using the multichannel analyzer set at 1024 channels. Longer counting times are necessary if smaller detectors are used, because intrinsic detector efficiency is approximately proportional to detector volume.[16] The spectra shown in Figs. 1 and 2 were collected for about one hour using either 1024 or 2048 channels.

Gamma-ray spectra of a dish, a thorium lantern mantle, and a container of salt substitute are shown in Figs. 1, 2, and 3, respectively. Because of the poor energy resolution that is characteristic of NaI(Tl) detectors, many peaks in the gamma spectra cannot be resolved. We, therefore, have added energy spectra in Figs. 1 and 2 measured with a high purity germanium detector (HPGe). Details not evident in the NaI(Tl) spectra are clearly seen in the HPGe spectra. A great advantage of the HPGe detector is its excellent energy resolution, compared with that of a NaI(Tl) detector. A major disadvantage is the relative cost (more than ten times higher) that makes the HPGe detector prohibitively expensive for many schools.

Background Radiation. Detected background in gamma spectra is due primarily to cosmic interactions and ambient gamma rays. This background is more prominent at low

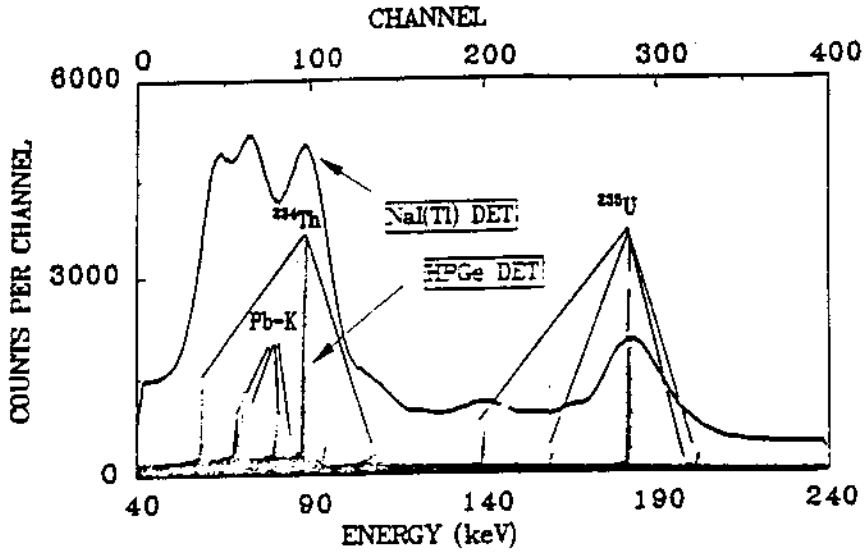


Fig. 1. Gamma spectrum of Fiestaware dish. The presence of ^{235}U is established from the five gamma peaks characteristic of its decay. The presence of ^{238}U is inferred from the gamma-decay peaks of its daughter ^{234}Th. Lead K-shell fluorescence x-rays are from the detector shielding.

energies.[16] Continuous low energy bremmstrahlung radiation may also contribute to the gamma spectra of beta emitters such as ^{40}K. The betas radiate this energy as they accelerate near atomic nuclei. Peaks due to x-ray fluorescence in lead are often observed in gamma spectra as well. These low-energy x-rays usually are produced when stray gamma rays from the source pass into the lead detector shield. Several K-shell x-ray fluorescence peaks are noted in the spectra shown in this paper.

Fiestaware Dish. Our main purpose in examining the gamma spectrum of the dish was to identify the uranium isotopes ^{235}U and ^{238}U. We accomplished this by displaying in Fig. 1 only the low-energy portion of the spectrum below 240 keV. The isotope ^{235}U can be identified by the cluster of five peaks in the HPGe spectrum. The gamma rays (whose energies are 143.893, 163.455, 185.835, 202.236, and 205.413 keV) accompany the alpha decay of ^{235}U to ^{231}Th. Broad peaks centered at about 144 keV and 186 keV in the NaI(Tl) spectrum cover the range of the five ^{235}U peaks contained in the HPGe spectrum.

The isotope ^{238}U does not emit gamma rays during alpha decay, so it could not be identified directly. There is, however, strong indirect evidence of the presence of ^{238}U provided by decay of its daughter ^{234}Th, which transforms by β-decay with accompanying gamma rays having energies 63.29 keV, 92.38 and 92.80 keV (unresolved), and 112.810 keV.[7] These gamma-ray energies, marked as peaks in the HPGe spectrum of Fig. 1, appear as possible (but not completely resolved) peaks in the NaI(Tl) spectrum. Other uranium-series peaks at 609 keV (^{214}Bi), 767 keV (^{214}Bi + ^{234m}Pa), and 1001 keV (^{234m}Pa) can be identified with either type of detector when the spectrum is extended to higher energies than shown in Fig. 1. However, a longer count time is required to observe them. Using long count times, we have succeeded in identifying nearly all of the gamma-emitting radionuclides in the natural uranium (^{238}U) and actinium (^{235}U) decay series with our HPGe detector.

Gas-Lantern Mantle. We used a Coleman™ "green top" thorium mantle in our study. The gamma spectrum of the thorium lantern mantle shown in Fig. 2 reveals a large number of peaks that are identified as members of the natural thorium decay chain. The parent ^{232}Th and its daughter ^{228}Ra are difficult to identify, even with the HPGe detector. This is because their gamma-ray energies are very weak in intensity and because the lead x-ray fluorescence peaks interfere. Probably the most convincing evidence of thorium-series decay to show students is the large ^{212}Pb peak at 238.633 keV. This peak is identified easily with either a HPGe or a NaI(Tl) detector. Complete gamma spectra up to 3000 keV for a thorium gas mantle have been published.[17,18]

Salt Substitute. The gamma spectrum of a 311-g (11-oz) container of NoSalt salt substitute shown in Fig. 3 contains a single 1461-keV peak from the decay of ^{40}K. We were able

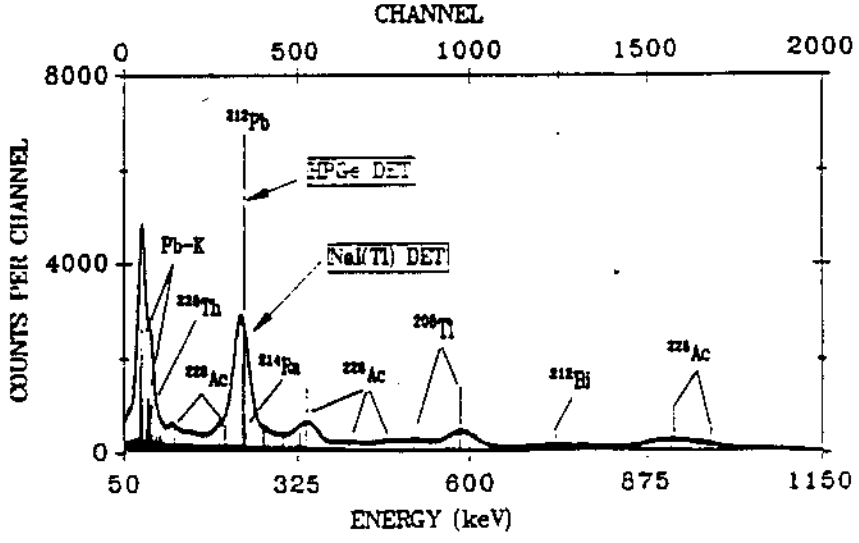


Fig. 2. Gamma spectrum of "green top" Coleman lantern mantle. Gamma peaks indicate the presence of many decay progeny of ^{232}Th, which is the parent radioisotope in the natural thorium decay chain. Lead K-shell fluorescence x-rays are from the detector shielding.

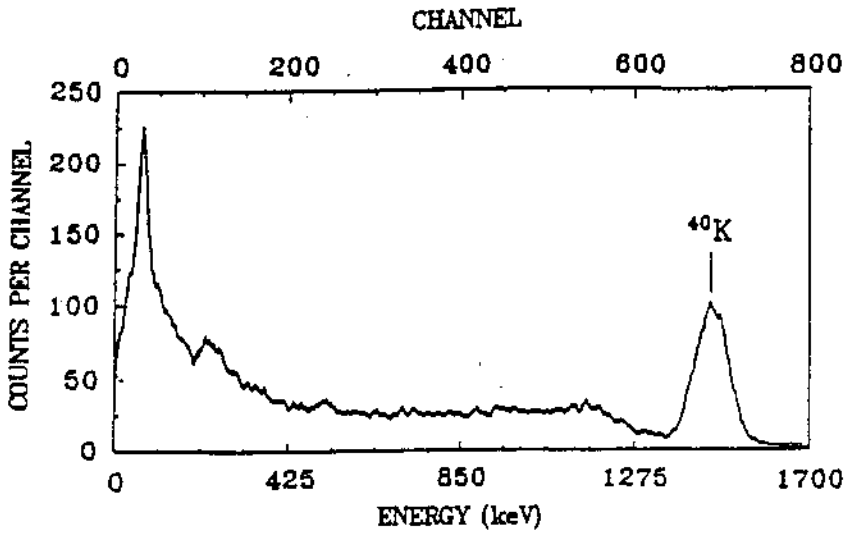


Fig. 3. Gamma spectrum of NoSalt. Single peak at 1461 keV is from ^{40}K.

to collect more than 700 net counts in that spectrum peak in under two minutes using our NaI(Tl) detector. As noted earlier, the background at low energies is high, mostly due to bremmstrahlung. The 217-keV backscatter peak can also be seen. We did not include an HPGe spectrum here because the single 1461-keV peak of ^{40}K is so easily identified with the NaI(Tl) detector.

Assessment of Hazards to Instructors and Students

Readers may wonder about the safety of using the dishes and mantles in the classroom. The glaze of orange-red dishes contains a relatively large amount of uranium, and green-top gas mantles contain an abundance of thorium. Principles of radiation safety in schools and labs have been discussed previously in *The Physics Teacher*.[19–22] Current Nuclear Regulatory Commission regulations for radiation safety and dose limits can be found in the latest annual printing of 10CFR20.[23] Teachers should be aware that a major revision in regulations went into effect January 1, 1994.

Internal Chemical Toxicity and Radiotoxicity

Uranium can leach out of the orange-red glaze of Fiestaware with food and chemicals of moderate acidity. Many fruit and vegetable products are quite acidic; for example limes (pH 1.8–2.2), apples (pH 2.9–3.3), and tomatoes (pH 4.0–4.4). In one study,[24] a red-orange dish was immersed for 24 h in a 4% acetic acid solution (pH of 2.4), which is comparable to household vinegar. Analysis showed 0.64 mg, or 16 Bq (430 pCi), of uranium present in 20 ml of leachant.

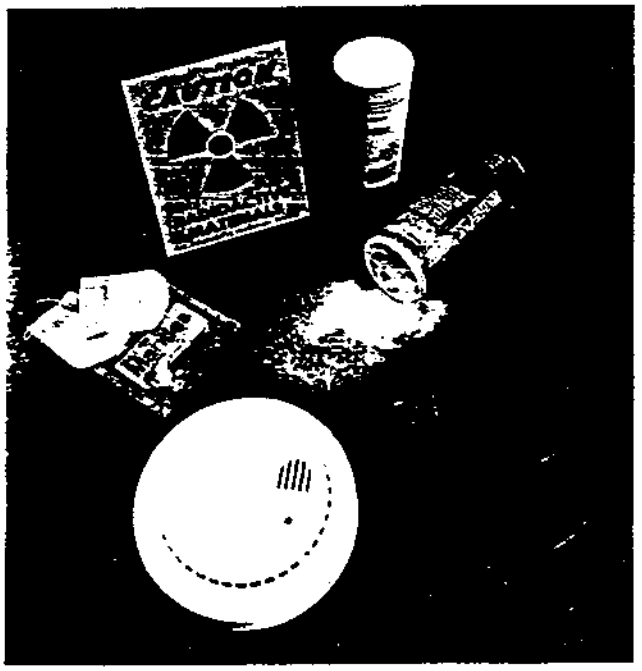
For large single intakes of uranium, chemical toxicity is of greater concern than radiotoxicity. Uranium is known to have chemotoxic effects on the kidney (nephritis) above certain single-dose thresholds.[25] Uranium also may result in radiotoxic effects on bone (sarcoma) from long-term exposure to alpha decay.

Lantern mantles are reported as having 300 mg of ^{232}Th, which corresponds to 1.2×10^3 Bq (3.3×10^4 pCi) of radioactivity per mantle.[3] This amount of radioactivity is 5% of the annual limit on intake for occupational exposure.[23] Oral ingestion of a mantle would exceed, by a factor of 2.5, the annual dose limit (0.02 of the occupational dose limit) to individual members of the public.

One extreme case of internal exposure that we might postulate is for a student to drink a cocktail of uranium leachant containing 0.64 mg U, the amount described above. The calculated dose over 50 y to bone surface tissue from this intake would be 20 μSv (2 mrem). For uranium at this level, observable chemotoxic effects would not be expected. Another postulated extreme case might be for a student to eat one lantern mantle. The calculated dose over 50 y to bone surface tissue would be 24 mSv (2.4 rem). So we see that if thorium is ingested in the amount contained in a lantern mantle, the accumulated lifetime internal dose can be appreciable. Every precaution should be taken to prevent ingestions of these materials.

External Radiation Effects

Radiation readings made with a GM detector may seem high near the dish or thorium mantle, but actual exposure rates are quite low. For dishes, the dose rate at contact is about 10 μSv h^{-1} (1 mrem h^{-1}). For mantles, the contact dose rate is about one-tenth as high. Most external radiation exposure results in beta dose to the hands and arms received from handling the dish or mantle. Some dose to the body from



Radioactive items. Photo courtesy of Marlin R. Wagner, freelance photographer, 226 Fair Street, Bloomsburg, PA 17815.

gamma radiation would also be expected. Alpha radiation does not penetrate the epidermis of the skin.

One study carried out by the U.S. Food and Drug Administration, referenced by Schuyler,[26] posited the existence of a restaurant that used uranium tableware exclusively, and then calculated that a person washing dishes in this establishment, working a full year of 40-hour weeks (with a two-week vacation) for a total of 2000 h, would receive an annual external radiation dose of 344 μSv (34.4 mrem). Based on this example, an instructor presenting a classroom demonstration or a student doing an experiment in which a dish is used for one hour would likely receive an external dose no higher than about 0.2 μSv (0.02 mrem). The external dose received from a single thorium mantle during a classroom demonstration or lab experiment would be roughly one-tenth the dose received from a dish, or about 0.02 μSv (0.002 mrem) for each hour of use.

Although radiation hazards may be small, teachers should still minimize exposures by practicing good health physics safety procedures. This would include handling sources no more than necessary, maintaining a maximum distance, storing them safely, and washing hands after handling sources.

Conclusion

Instructors who use radioactive consumer products in teaching radiation concepts will find information here that will help them enliven their radioactivity demonstrations and experiments. We conclude from quantitative estimates that potential chemical and radiation hazards to teachers and students are minimal as long as reasonable precautions are followed.

Radiation Units[20,23]

The units of radioactivity are the becquerel (Bq) and the curie (Ci).

- 1 Bq = 1 transformation per second
- 1 Ci = 3.7×10^{10} Bq
- 1 g of ^{226}Ra has an activity of 1 Ci

Absorbed radiation dose, when applied to human body tissue, is called dose equivalent. The units of dose equivalent are the Sievert (Sv) and the rem.

- 1 Sv = 1 J kg^{-1} (1 joule radiation energy absorbed per kg tissue)
- 1 rem = 100 erg g^{-1}
- 1 Sv = 100 rem

Annual radiation dose equivalent limits (excluding background and medical exposures):

- 50 mSv (5000 mrem) for occupationally exposed workers
- 1 mSv (100 mrem) for the general public, including students

Common exposures to the general public[7,11,27]

- Natural background, 3.5 mSv (350 mrem) annually (2.9 mSv radon and progeny, plus 0.6 mSv all other combined)
- Five-hour transcontinental flight, 0.01 mSv (1 mrem)
- Average chest x-ray, 0.1 mSv (10 mrem) to bone marrow
- Average dental x-ray, 0.09 mSv (9 mrem) to bone marrow

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