Radiation Sources Fabricated from Kelp Powder for Educational Purposes

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Kelp contains naturally occurring radioisotopes. Edible kelp flakes were used to fabricate a disk-shaped radiation source by a method involving compression and formation. This method is suitable for fabricating kelp radiation sources and does not require any special skills or techniques. The kelp radiation sources were used in an educational course on radiation and their suitability for use in the classroom was assessed by performing two tests on the dependence of the radiation count rate on distance and shielding. The distance dependence test demonstrated that the relationship between distance and radiation count rate could be explained by the inverse-square law, while the shielding dependence test showed that the shielding effectiveness increased with mass density and that the radiation count rate decreased exponentially with shielding thickness. It was concluded that the compression and formation method was suitable for fabricating kelp radiation sources that are effective educational tools for illustrating the existence of naturally occurring radioisotopes and demonstrating the principles of radiation protection.

Key words: K-40 natural radioisotope, kelp, radiation source, compression and formation, teaching aid

1. Introduction

Many materials contain naturally occurring radioisotopes such as $^{40}$K, $^{232}$Th, and $^{238}$U. Such materials include monazite, sinter (hot-spring deposit), chemical fertilizer, and kelp. These materials are often used in educational courses on radiation since they are well-known materials that contain natural radioisotopes. In the present study, a disk-shaped radiation source was fabricated from kelp. It is expected to be useful not only for finding out about natural materials that contain radioisotopes but also for demonstrating the radiation protection principles of distance and shielding. For a radioactive source to be used safely and easily in educational courses on radiation at junior and senior high schools and in community education, it should be fabricated from materials that students are very familiar with and can obtain easily. For use in actual experiments in educational courses, the fabricated radiation sources should be sufficiently hard and resilient to rough handling, and have a radioactivity that is sufficiently high to be clearly distinguished from background radiation levels. The source should be an appropriate size for handling and it should have a smaller diameter than the radiation detector.

With the aim of developing such a radiation source for educational use, a method involving compression and forming has recently been developed. This method does not alter the amount or the radioactivity of the material; rather it reduces the volume of the material. In the present study, this method (which we term the compression and formation method) was applied to commercially available kelp to fabricate several radiation sources. The fabricated sources were inspected to evaluate the suitability of the method. The suitability of the sources for use in educational courses on radiation was then examined by performing two tests on the dependences of the count rate on distance and shielding. Hereafter, these radiation sources fabricated from kelp are referred to as kelp radiation sources.
2. Method for fabricating radiation sources and its suitability

2.1 Kelp and potassium

Kelp is a large, brown seaweed that grows in the seas of the north coast of Japan, including coastal areas of Aomori Prefecture and Hokkaido. Kelp contains various minerals, including sodium, potassium, and calcium. Of these minerals, potassium is unique in that a proportion of it is the radionuclide, $^{40}\text{K}$\(^{11, 12}\).

Naturally occurring potassium exists as three isotopes: $^{39}\text{K}$, $^{40}\text{K}$, and $^{41}\text{K}$; their abundance ratios are 93.258%, 0.0117%, and 6.730%, respectively\(^{13}\). Of these isotopes, only $^{40}\text{K}$ is a radionuclide; it emits beta particles as a result of beta decay (89%) and gamma radiation due to electron capture (11%). Beta decay emits beta particles with a maximum energy of 1.33 MeV and electron capture results in a 1.46-MeV gamma ray being emitted; these nuclear processes produce the stable isotopes $^{40}\text{Ca}$ and $^{40}\text{Ar}$, respectively. The half-life of $^{40}\text{K}$ is $1.28 \times 10^9$ years, which means that the change in its radioactivity is negligible over a human lifetime. Thus, a kelp radiation source could be used indefinitely.

In the present study, kelp flakes, which are generally sprinkled on cooked rice, were purchased at a shopping mall and used as the raw material. The kelp flakes were produced by mixing the three most common kelp species ($\textit{Laminaria ochotensis}$ (Rishiri konbu), $\textit{Laminaria religiosa}$ (Hosome konbu), and $\textit{Laminaria longissima}$ (Naga konbu)) with other additives such as sweeteners, acidic ingredients, and flavors. The compression and formation method was applied to the flakes. The kelp flakes are very safe because they are edible. Consequently, the fabricated kelp radiation sources should be safe to handle, since they were formed by simply pressing and forming a safe, edible material.

Table 1 shows the elements that were identified by inspecting the kelp flakes by fluorescence X-ray analysis (Rigaku, ZSX100e). The results reveal that 3.31% of the kelp is potassium. Furthermore, a gamma-ray spectrum was obtained using a NaI scintillation detector (see Fig. 1). This spectrum was obtained by subtracting a background spectrum from a spectrum of the kelp sample. Both spectra had measurement times of 100,000 sec. The spectrum in Fig. 1 has one main peak at 1.46 MeV, which corresponds to gamma emission from $^{40}\text{K}$, and a small peak at 2.61 MeV, which is the peak of a naturally occurring radionuclide $^{208}\text{TI}$ in the thorium series — this small peak may be caused by errors in the spectrum subtraction procedure.

2.2 Method for fabricating kelp radiation sources

To fabricate a kelp radiation source, the kelp flakes were
dried and micronized with a pulverizer (Retsch Technology GmbH, MM 200). An amount of kelp powder was weighed with a direct-reading balance (Sartorius, BP121S), and then placed in a cylindrical stainless-steel formwork (inner diameter: 35 mm, height: 30 mm). The kelp powder in the formwork was compressed with a force of approximately 160 kN by using a hydraulic hand pump (Osaka Jack Co. Ltd., TW-0.7) and a jack (Osaka Jack Co. Ltd., NT20S12.5). A disk-shaped solid cake was obtained.

By consistently using this method, six sources were fabricated from six different masses of kelp (2, 3, 5, 10, 15, and 20 g) and their thicknesses, diameters, and mass densities were measured. The direct-reading balance was used to measure the mass, which was used to determine the mass density, and a Vernier micrometer was used to measure the thickness. The results are shown in Fig. 2, in which the thickness (denoted by squares) increases linearly according to the equation \( Y = 0.698 \times X \). However, this equation became \( Y = 0.708 \times X \) when the data for the two smallest sources (the 2 and 3 g sources) are excluded. This might be because the thicknesses of the thin sources were slightly overestimated due to the difficulty of accurately measuring their thicknesses, although this is not apparent in Fig. 2 (see the following paragraph). Nevertheless, the above two equations do not differ by much so that they can be used to estimate the thickness of a source from the mass of kelp used. This result confirms that the thickness of the source formed by the compression and formation method varies consistently with the initial amount of kelp used. The linear relationship between thickness and mass demonstrates that the compressibility ratio is constant, being independent of the amount of material used. The radioactivity distribution is assumed to be uniform over the source because the kelp is uniformly compressed.

The rhombus symbols in Fig. 2 denote the measured diameters. They form a horizontal line indicating that the diameters of the fabricated sources are very stable and do not vary with the mass of kelp used. The average of the six diameters is 35.37 mm and its relative standard deviation (RSD) is 0.13%. The mass density (denoted by triangles) is also stable, although the values for the 2 and 3 g sources are a little low. These underestimations are presumably caused by overestimating the thickness of these two sources, as mentioned in the previous paragraph. The average mass density of the sources, excluding the 2 and 3 g sources, is 1.46 g/cm\(^3\), with an RSD of 0.80%, whereas the average mass density for all six sources was 1.44 g/cm\(^3\), with an RSD of 2.61%. There is not a large difference between these two mass densities.

Based on the above results, the compression and formation method is considered to be suitable for fabricating kelp radiation sources, especially when more than 5 g of kelp flakes is used.

### 2.3 Saturation thickness of kelp radiation source

The total radioactivity of the source should be proportional to the mass of kelp flakes used. However, the radioactivity measured by the detector was not always proportional to the mass because some radiation emitted within the source material is absorbed within the source material itself (a process known as self-absorption). The stopping probability should increase with the thickness of the fabricated source. Consequently, the count rate measured by a detector will not increase if the thickness exceeds a certain saturation thickness.

To determine the saturation thickness, 16 sources with different thicknesses were fabricated by using different combinations of the six sources described in Section 2.2 and their radioactivity was assessed by measuring their count rates. The count rate was obtained over a 10-min integration in which a kelp radiation source was placed against the center of the survey meter probe. In the present measurement, a Geiger-Mueller (GM) survey meter (Aloka, TGS-146) was used as an integration counter. The diameter of its probe is about 50 mm, which is significantly larger than the diameter of the kelp radiation sources (35 mm). Figure 3 shows a schematic diagram of the measurement setup. In these measurements, the distance is defined as the distance between the surfaces of the probe and the source. Thus, the measurements described in this section were performed with the distance set to zero. The net count rate from the kelp radiation source was derived by subtracting the background count rate (42.7 cpm) from that of the source.
Figure 4 shows the relationship between the measured count rate (y-axis) and the source thickness (x-axis). The count rate initially increases as the thickness increases, but it begins to plateau for thicknesses in the range 10–14 mm. A thickness of 14 mm could be taken as the saturation thickness. For thicknesses over 14 mm, the count rate remains constant within the standard deviation, which is indicated by the error bars in Fig. 4. The saturation thickness of 14 mm corresponds to about 20 g of kelp. The count rate after the thickness saturation is about 70 cpm, which is over 1.5 times greater than the background count rate. This count rate should be sufficiently high to distinguish it from background radiation.

3. Dependency tests using kelp radiation source

Two tests relating to distance and shielding were performed to determine if the kelp radiation sources are suitable for use in educational radiation courses. The kelp radiation source used in the tests had a weight of 20.0 g, a thickness of 13.9 mm, a diameter of 35.4 mm and a radioactivity of 20.0 Bq. The radioactivity was calculated based on Table 1. The net count rate from the kelp radiation source was derived by subtracting the background count rate measured without the source from that with the source. An integration time of 10 min was used in both tests, which is the same integration time as that used to determine the saturation thickness. For an actual educational radiation course, the integration time for a single measurement should preferably be 1 min or less to allow many data points to be obtained. However, an integration time of 10 min is still acceptable because several measurements can be performed in a one-hour class.

3.1 Distance dependence test

Net count rates were obtained at 11 distances in the range 0 to 30 cm. The results are shown in Fig. 5, where circles indicate the count rates measured as a function of distance. An initial steep decrease in the count rate was followed by a more moderate decrease with distance in accordance with the inverse-square law. For reference, a typical inverse-square curve, \( Y = A/(a + X)^2 \), is also plotted in Fig. 5, where \( X \) is the distance and \( Y \) is the count rate, and \( A \) and \( a \) are constants with values of 500 cpm·cm\(^2\) and 5 cm, respectively. These values were determined by fitting the curve to the data points in Fig. 5 by trial and error. The physical meaning of the constant \( a \) is the effective depth from the detector surface to the point where radiation is detected. Since the measured count rates are distributed about the curve, the experimental results can be semiquantitatively explained by the inverse-square law.

3.2 Shielding thickness dependence test

The dependences of the shielding effectiveness on the thickness and type of material used were examined using paper, plastic, and aluminum. Kent paper (thickness: 0.25 mm, mass density: 0.93 g/cm\(^3\)) was used as shielding paper. Similarly,
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commercially available plastic sheets (vinyl chloride resin, thickness: 0.4 mm, mass density: 1.35 g/cm³) and aluminum plates (thickness: 0.5 and 1.0 mm, mass density: 2.7 g/cm³) were selected as shielding materials. The paper sheets, plastic sheets and aluminum plates were cut into 50 × 50-mm² sheets or plates and they were stacked to produce shielding of various thicknesses (0.5, 1, 2, 4, and 8 mm).

During this test, the distance between the kelp radiation source and the probe of the survey meter was fixed at 15 mm (see Fig. 3). Shielding materials of various thicknesses were placed between the source and probe and the net count rate was measured with the GM survey meter. The respective transmissions were obtained by dividing the shielded net count rates by the unshielded rates. Transmissions for the 0.5-mm-thick and 1-mm-thick plastic sheets were estimated by interpolating the values obtained for plastic plates with thicknesses of 0.4 and 0.8 mm, and 0.8 and 1.2 mm, respectively.

Figure 6 shows the transmission results. It shows that all the transmissions decrease dramatically at first and then moderately as the thickness increases. The rate of decrease is in order: aluminum > plastic > paper. Since the mass densities of aluminum, plastic, and paper are respectively 2.7, 1.35, and 0.93 g/cm³, the results demonstrate the general principle of radiation shielding that materials with a larger mass density provide greater radiation shielding. This experiment semiquantitatively demonstrates the relationship between the mass density and the effectiveness of shielding against radiation.

The radionuclide ^40^K emits a 1.33-MeV beta particle and a 1.46-MeV gamma ray after disintegration. To determine which of these two radiations the GM survey meter mainly counts, the transmission for a 0.5-mm-thick aluminum shield was examined. If the GM survey meter principally detects gamma rays, the transmission will conform to:

\[ Y = e^{-\mu t \cdot (X)}, \]

where \( X \) is the thickness, \( Y \) is the transmission, \( \rho \) is the mass density of aluminum (2.7 g/cm³), and \( \mu m \) is the mass absorption coefficient of aluminum for 1.46-MeV gamma rays (0.05 cm²/g)\(^12, 15\). Consequently, \( Y \) was determined to be 0.935. This result is not consistent with the results for aluminum shielding shown in Fig. 6.

Next, assuming the GM survey meter principally detects beta particles, the maximum range traveled by the most energetic beta particle was calculated using the following equation:

\[ R = 0.542E_{\text{max}} - 0.133 \]

\( R \): g/cm², \( E_{\text{max}} \): maximum energy of beta particles (MeV)

Equation (2) is often used to determine the maximum range of beta rays (R) for maximum energies (\( E_{\text{max}} \)) larger than 0.6 MeV\(^16\). In the case of ^40^K, \( E_{\text{max}} \) is 1.33 MeV which gives \( R = 0.588 \) g/cm². This gives a thickness of 6.32 mm for paper, 4.35 mm for plastic, and 2.18 mm for aluminum. Almost the same thicknesses can be derived from Fig. 6. These results demonstrate that the count rate measured by the GM survey meter can mainly be attributed to beta rays. This result demonstrates that experiments for measuring the range of beta rays can be performed using the kelp radiation sources.

Fig. 6  Dependence of transmission on shielding thickness and type of material.
In Fig. 6, the three curves represent the exponential function:

\[ Y = e^{-\beta m X} \]  

where \( X \) is the thickness, \( Y \) is the transmission, \( \rho \) is the mass density of the shielding material, and \( \beta_m \) is the mass absorption coefficient for beta particles (beta mass absorption coefficient), which are 0.96, 1.11, and 1.11 cm\(^2\)/g for paper, plastic, and aluminum, respectively. These coefficients are estimated by fitting Eq. (3) to the data in Fig. 6 by trial and error. The transmissions measured for the plates lie along their respective exponential curves. This result semiquantitatively demonstrates that the shielding effectiveness varies exponentially with the thickness of the shielding. The inset of Fig. 6 shows a semilogarithmic plot of the transmission of paper against the thickness. This result explains that the semilogarithmic plot of the transmission of paper shows a straight line with the x-axis16, 17) is approximately equal to the beta-particle range (about 6 mm from the inset of Fig. 6). This thickness is nearly equal to the range calculated using Eq. (2).

In addition, it was examined if an experiment to determine the half-value layer of material for beta particles could be conducted in an educational course on radiation based on the transmission data for paper shown in Fig. 6. From Eq. (3), the equation for calculating the half-value layer \( (X_{1/2}) \) is derived as:

\[ X_{1/2} = \frac{0.693}{\rho \beta m} \]  

Using Eq. (4), the half-value layer of paper for beta radiation can be calculated in the following manner. By substituting the values of the mass density (0.93 g/cm\(^3\)) and the mass beta absorption coefficient (0.96 cm\(^2\)/g) into Eq. (4), the half-value layer of paper was determined to be 0.78 mm. This result is reasonable from Fig. 6. Thus, the kelp radiation sources can be used to explain the concept of the half-value layer as a characteristic of radiation shielding.

The above results demonstrate that a kelp radiation source is useful for demonstrating the relationships between radiation intensity and distance, radiation intensity and shield thickness, and radiation intensity and the mass density of shielding materials. Furthermore, the kelp radiation source can be used to examine the range of beta particles and the half-value layer of shielding material. The kelp radiation source will illustrate the existence of naturally occurring radioisotopes to students of a basic radiation course and demonstrate the principles of radiation protection.

4. Evaluation from a practical standpoint

To evaluate practical suitability of the kelp radiation source for use in an educational radiation cause, its robustness, secular change, and smell were examined. The sources used in the present study were all fabricated in October 2007. Subsequently, the sources were placed in an ordinary plastic container and stored in a normal room that was cooled and heated by a conventional air conditioner, which was operated when the room was occupied. The kelp radiation sources were used many times in the present study and at demonstrations in educational courses on radiation and conference presentations. During this period, no deterioration or problems were encountered with respect to their brittleness or hygroscopicity. During normal handling the edges of the kelp radiation sources did not chip, even without taking special precautions.

The kelp radiation source has the same smell as common kelp; this smell is not strong. However, if the kelp radiation sources were stored together with other materials in the same plastic container, the other materials might absorb the smell of the kelp. The container we used was also used to store radiation sources fabricated from mushrooms. The mushroom radiation sources were stored with the kelp radiation sources for several weeks in the same container and they started to smell like kelp.

It is concluded that the radiation sources fabricated from kelp are very suitable from a practical perspective and that they can be used for normal use without any problems, except for the minor problem of smell transfer.

5. Summary

A radiation source was developed from kelp flakes, which are generally used to sprinkle on cooked rice. The kelp flakes contain the naturally occurring radioisotope, \(^{40}\)K. A method involving compression and formation was used to fabricate the kelp radiation sources.

It was found that the compression and formation method was a convenient way to fabricate kelp radiation sources and that it does not require special skills or techniques. Using the kelp radiation source, the dependences of the count rate measured with a GM survey meter on distance and shield thickness were evaluated. The test investigating the distance dependence demonstrated that the inverse-square law applies to the distance between the source and detector. The shielding dependence test demonstrated that there was an exponential relationship between the shielding effectiveness and the thickness of the shielding material. In addition, the shielding effectiveness increased with the mass density of the material and the beta-particle range and
half-value layer of the shielding material determined from experimental data almost coincided with theoretically derived values.

The robustness, secular change, and smell of the kelp radiation sources were also examined. Two years after they had been fabricated, no deterioration or problems were found in terms of brittleness and hygroscopicity. The edges of the kelp radiation sources did not chip during normal handling. The only problem is that materials stored with the kelp radiation sources absorb the kelp smell.

The kelp radiation source will be a useful aid for courses on radiation and its characteristics and it will allow students to easily experience radiation and better understand its characteristics.

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