FOOD PRESERVATION BY RADIATION

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INTRODUCTION

In the USA, in spite of a safe and abundant food supply that is the envy of the world, bacteria-tainted food needlessly causes the death of about 9,000 persons per year. About 6.5 million serious cases of food related illness occur each year. A figure of food borne illnesses has been claimed in the 200 to 250 million cases per year range. A characteristic of food borne disease is that it has an incubation period before symptoms can be noticed.

Irradiation is the most effective method capable of eliminating the deadly new mutation known as E. Coli 0157:H7 bacteria in raw meat. It can also significantly reduce levels of other pathogens, including Listeria, Salmonella, Shigella, Campylobacter and others.

While there is no single technique to cure all food problems, irradiation is accepted as both safe and effective. It has been approved for raw beef, pork and lamb as well as poultry and other food products.

In the USA, the regulatory agencies involved in food irradiation are the US Department of Agriculture (USDA) and the Food and Drug Administration (FDA). Irradiated foods are to be labeled by the international symbol of irradiation, known as the Radura shown in Fig. 1, and a statement that they were irradiated. The symbol is colored green on a white background, and includes two leaves resting on a semicircle, with a green dot above it beneath a broken-lined semicircle.

Fig. 1: The International Radura symbol for food irradiation.

FOOD SPOILAGE AND POISONING

Food spoils because of complex physical, chemical and biological deterioration as well as through the activities of microorganisms and insects. For best nutrition, foods should be eaten as close to the time of harvest as possible. Once a plant or animal is dead, decomposition immediately begins, and its nutrients content is decreased. Living tissue ultimately decays to carbon dioxide, minerals, water and ammonia from which its organic molecules are composed.

As food is bruised in picking, microorganisms invade it. Molds and yeasts find a fertile ground in sugars converting them into alcohol through fermentation. Fruit flies are attracted to the alcohol, carrying vinegar bacteria, which burn up the alcohol. These processes demolish the structure of the food and spoil it.

Cases of food poisoning arise from intestinal infections caused by bacteria. Table 1 shows some of the bacterial agents causing food poisoning together with their sources, incubation period, and disease symptoms duration.

Table 1: Some bacterial agents causing food poisoning.

Bacterial Agent	Source	Duration of symptoms	Incubation period
Campylobacter	Undercooked poultry	2-10 days	2-5 days
E. Coli 0157:H7	Undercooked beef, raw produce	4-7 days	1-3 days
Listeria monocytogenes	Deli meat, hot dogs, unpasteurized dairy	-	-
Salmonella	Undercooked eggs, or poultry..	4-7 days	1-3 days
Shigella	Raw produce, egg salad	4-7 days	1-2 days
Staphylococcus aureus	Meat, potato and egg salad	1-2 days	1-6 hours
Yersinia enterocolitica	Undercooked pork	1-3 weeks	1-2 days

The most common food borne disease is caused by Staphylococcus aureus. This bacterium is common on the human skin and in the nose and throat. Infection by this organism begins suddenly, but victims recover after several days. The prevention requires cleanliness, proper cooking and preservation through some food preservation means such as drying, canning, or freezing.

Food poisoning can result from the Salmonella and Shigella bacteria found in eggs, poultry, sheep and cattle feces, insects, and the intestines of humans and animals. Their effect is felt 12 to 24 hours after the food is ingested. These are not serious illnesses, and people recover within days.

A parasite Trichinella spiralis (Trichinea) is often found in pork products. The larvae of the parasite, Trichinea, are destroyed by cooking, by radiation, or by keeping the meat below freezing for over 20 days. This can lead to serious sickness, even though it is common.

A toxin formed in foods by the bacterium Clostridium botulinum causes a rare and most serious form of food sickness. This bacterium lives in soils and is not harmful, except when it multiplies under anaerobic (without air) conditions in foods. The only known treatment for botulism is to use an antitoxin, with death resulting if the disease is not diagnosed soon enough, and the antitoxin administered. This is more common in home canned foods than in commercial foods.

Lately, a new mutation or variant of the E. Coli bacteria has caused numerous deaths as a result of the contamination of meat production by intestinal feces during the slaughtering process: the deadly E. Coli 0157:H7. Irradiation is the most effective means to eliminate it.

A new infective agent : prions is thought as the cause of mad cow disease or Bovine Spongiform Encephalopathy (BSE) which is similar to the Creutzfeld Jacob Syndrome in humans. With symptoms resembling Alzheimer's disease, it destroys the brain cells of the victims. This unfortunately cannot be affected by radiation since it is primarily caused by a protein, and the only way for prevention is to avoid the use of any contaminated foods.

IRRADIATION STATUS

More than 35 countries worldwide allow the irradiation of food. In the USA, in addition to raw beef, pork and lamb, spices, wheat, flour, potatoes, pork, poultry, fruits, and vegetables, have been irradiated. Irradiation was approved to control Trichinea in pork in 1990, Salmonella in chickens in 1994, and E. coli in raw meat in 1999.

In Canada, irradiation is used to prepare meals for hospital patients. Cancer patients in particular cannot tolerate a dose of E. coli 0157:H7. French food processors also use irradiation.

The World Health Organization (WHO) designated food irradiation as a perfectly sound food preservation technology that is needed in a world where food borne diseases are on the increase, and where in between 1/4 to 1/3 of the global food supply is lost post-harvest.

The USA National Food Processors Association accepts it as a greater degree of protection for all consumers, especially the most vulnerable: young children, the elderly and the immune-compromised. The American Medical Association (AMA) is on record as supporting food irradiation.

Since the 1960s, the National Aeronautics and Space Administration (NASA), included irradiated foods on the menus of its space flights. These foods were found to be as nutritious as non-irradiated foods. In addition, these foods pose no risk of food borne illness to the astronauts, since irradiated foods are free of any harmful bacteria.

IRRADIATION FACILITIES

There exits many commercial irradiation facilities in the USA. Isomedix, an irradiation company in Whippany, New Jersey, operates 14 irradiation plants in the USA, Canada, and Puerto Rico. These facilities primarily sterilize disposable medical products such as disposable syringes and gowns, and a broad range of consumer products including baby-care products.

Two other commercial companies operate in the USA. SteriGenics International in Tustin, California, and Food Technology Service Inc. (FTSI) in Mulberry, Florida, both irradiate food in the USA.

SteriGenics started in 1986 irradiating dry-food items such as pepper, onion powder, and dehydrated vegetable powder. About 50 million pounds of spices are irradiated each year.

Two methods are used to irradiate food products.

GAMMA RAY IRRADIATION:

Uses sources of gamma rays such as Cesium^{137} or Cobalt^{60}. Gamma rays can penetrate the food product to a great depth exposing the pathogens in deep layers of the irradiated product. Gamma irradiation machines can irradiate whole pallets of food products. Such a machine has a large capacity but low speed. The process is better than any means of pasteurization currently available, even though it is not 100 percent effective.

The radiation source is normally Cobalt^{60} pencils installed on either side of an 8 by 16 foot stainless steel rack. The pencils are stainless steel tubes containing two zirconium alloy tubes that encapsulate nickel-coated pellets of Cobalt^{60}.

LINEAR ACCELERATOR IRRADIATION:

A linear particle accelerator is used to create an electron beam, which would kill 99.9 percent of the pathogens in meat. The electron machine is high speed, but low capacity as compared with the gamma ray machine. This device generates a beam of electrons that directly contact the product, or convert the accelerated electrons into x-rays which can penetrate the irradiated product deeper, but are less efficient than the electron beam.

As an example, a Circe-3 irradiator built by Thomson CFE in Saint-Gobin, France, is used experimentally at Iowa State University. This accelerator comprises an electron gun consisting of a cathode and anode that generate electrons, which are pulsed in an accelerating tube. At the same time, radio frequency power is pulsed into the tube by a klystron, forming waves that the electrons follow. A series of alternating magnets in the tube accelerate the electrons to the high energy levels required for irradiation. At the end of the tube, they pass through a Glaser lens that focuses them into a beam. The beam is bent by a magnet by 107 degrees, so as to choose only those electrons from a specific energy range. Those filtered electrons pass through a scanning magnet and sweep across the irradiated product surface. Several energy levels can be selected at: 5, 7.5, and 10 MeV. These can penetrate, 3/4, 1, and 1.5 inches on one side, respectively. If both sides are irradiated, the penetration is 1 3/4, 2 1/4 and 3 1/2 inches respectively.

In either approach to irradiation, as shown in Fig. 2, the product, usually already packaged, is loaded onto a conveyor belt and is moved toward an irradiation room, which is a concrete bunker that contains the radioactive source.

The cell walls and ceiling are 6 1/2 foot thick concrete poured around steel rebar to ensure that no cracks can penetrate the walls.

When the product enters the room on the conveyor belt, a technician at the control console pushes a lever and the rack is lifted into the room. Everything entering this room is exposed to the radiation for a predetermined interval of time, usually in the few minutes range, depending on the nature of the product, its density, thickness, and other factors.

In the case of gamma irradiation, the radioactive source is lowered into a storage pool containing deionized water as a shielding material. The pool is 26 feet deep. Figure 3 shows the design of an irradiator research facility. Figure 4 shows a Cobalt^{60} gamma radiation source shielded under water, and Fig. 5 shows the source raised to irradiate a product.

After irradiation, the product moves out of the room along a conveyor belt. It can be handled immediately by workers since it does contain any residual activity, and is loaded onto trucks for shipping.

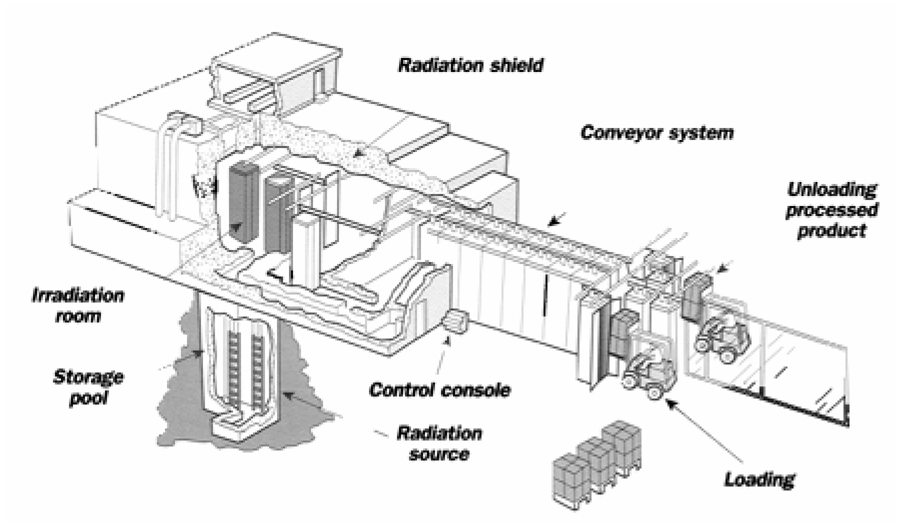

Fig 2: A typical Gamma Irradiation Facility.

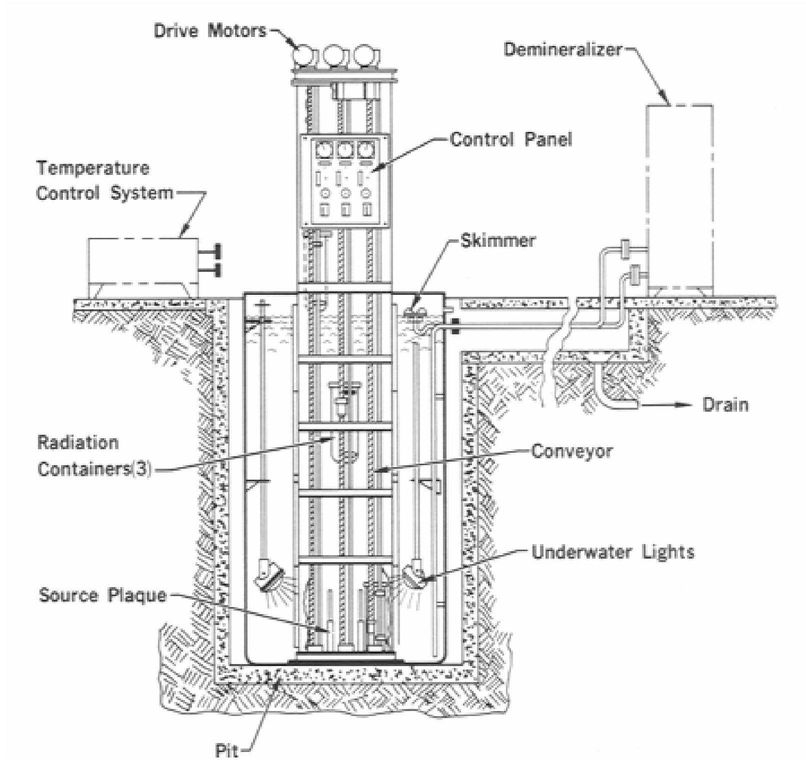

Fig. 3: Water shielded irradiator configuration.

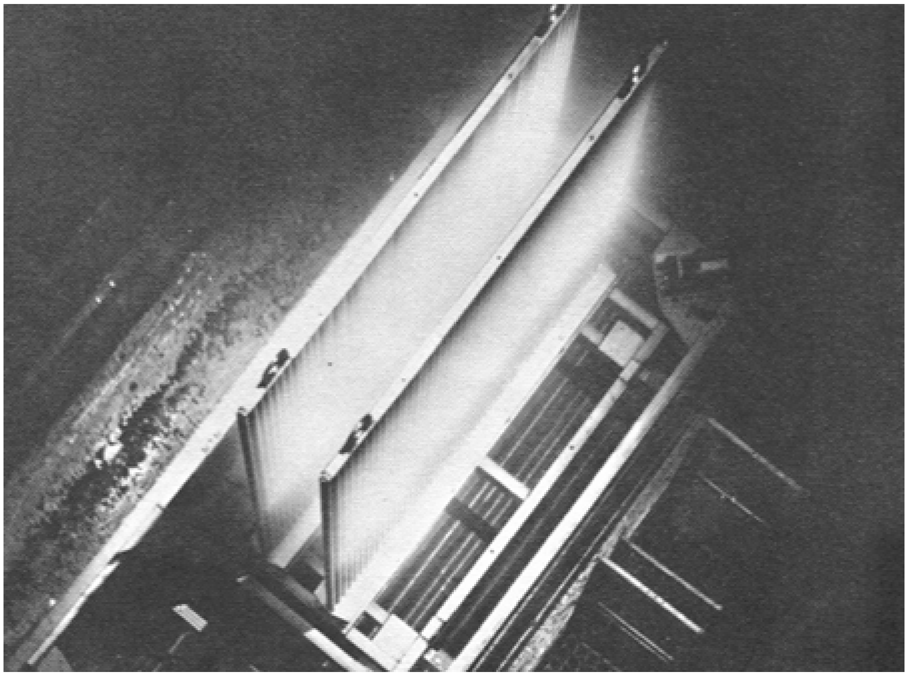

Fig. 4: A $Cobalt^{60}$ irradiation source under water shielding emitting Cerenkov radiation.

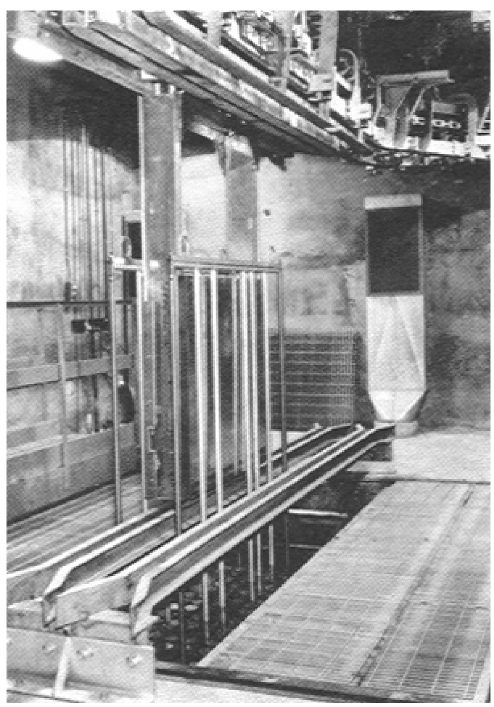

Fig 5: A conveyor rack passes between the raised $Cobalt^{60}$ rods at US Army Natick Labs food irradiator.

DOSAGE CONSIDERATIONS

If an atom is bombarded with radiation having sufficient energy to strip the electrons from the atoms away, the neutral atom is converted into a positively charged particle, or ion. Radiation moving through food ionizes some atoms in its path and causes an alteration of vital macro molecules which results in the destruction of bacteria and other microorganisms. The degree of ionization is proportional to the amount of energy deposited per unit mass of the material, or radiation dose.

If ionization occurs in food atoms, they do not become radioactive. With low doses of radiation, there is less loss of vitamins than in canning, freezing, or drying. At higher radiation doses, some vitamins are lost, but these can be replaced as they are sometimes replaced in other processed foods.

Dosage is controlled by the speed of the conveyor belt in an irradiation facility. For beef, the approved dose is 4 kilogray (kGy) in chilled meat, and 7 kGy in frozen meat. The maximum dose for spices is 30 kGy.

The absorbed dose unit of Gray (Gy) in the SI system of units delivers an energy equivalent in Joules per kilogram of the irradiated product as:

$$1 \text{ Gray [Gy]} = 1 \text{ [Joule/kg]}, \qquad (1)$$

$$\text{with: } 1 \text{ kGy} = 1{,}000 \text{ Gy}.$$

Another measurement unit for the radiation dose in the conventional system of units is the radiation absorbed dose or rad where:

$$1 \text{ rad} = 100 \text{ [ergs/gm]}. \qquad (2)$$

The relationship between the Gray and rad units is:

$$1 \text{ Gy} = 100 \text{ rads}, \qquad (3)$$

$$\text{and: } 1 \text{ kGy} = 100{,}000 \text{ rads}$$

Fresh vegetables, including avocados, onions, celery, bell peppers, and broccoli that are sold for retail sale or used for other products such as salsa, require a lower dose of less than 1 kGy of radiation. The shelf life of these products can be extended by up to two weeks.

Radiation preservation of food can be accomplished through two processes:

1. Pasteurization:

This is accomplished with low doses of radiation in the range of 2-5 kGy, and is used for prolonging the shelf life or storage time.

2. Sterilization:

Requires high level doses in the range of 20-45 kGy, and allows long term storage without refrigeration.

Different foods have optimal radiation doses for preservation, as shown in Table 2.

Table 2: Radiation Doses for different Preservation Options.

Food	Dose (kGy)	Effect
Potatoes, Onions	0.04-0.10	Sprout Inhibition
Grains, Cereals	0.20-0.50	Disinfection from insects
Fruits	0.50-3.00	Sterilize larvae of lodging insects
Fish	2.00-8.00	Extend shelf life up to 30 days
Meats: Beef, Poultry	45.00-56.00	One year storage at room temperature.

TOXIC CHEMICALS, FOOD POISONING AND QUARANTINES

The Florida Citrus Commission has sought an alternative to methyl bromide as a quarantine treatment for citrus. It was acting on an Environmental Protection Agency (EPA) suggestion that by 2001, it would ban this chemical, which is used to prevent the spread of fruit flies. This led to the formation of the second food irradiation company: FTSI, which started in 1992 treating packaged products for local and national brokers and distributors.

In addition to avoiding the use of toxic chemicals, irradiating addresses concerns of public health such as food poisoning. The process extends shelf life. It eliminates sprouting in tubers such as potatoes, garlic, and onions. It delays the ripening of some fruits and vegetables such as strawberries, tomatoes and mushrooms.

As an example, the storage life of fresh strawberries is normally 7 to 10 days. This can be effectively extended to two weeks after 2 kGy of radiation dose. There is a small loss of the vitamin C content, but it is of little nutritional value. Figure 6 shows the difference between an irradiated strawberry batch at 2.15 kGy or 215,000 rads, and an unirradiated control.

Fig. 6: Difference between an irradiated and an unirradiated control.

As a quarantine measure, irradiation kills the larvae of insect pests such as fruit flies and seed weevils in mangoes, preventing them from spreading across national borders or between growing regions in a given country.

SAFETY CONTROL SYSTEMS

Safety controls and interlocks are provided for food irradiators to protect the operating personnel and members of the public.

A major manufacturer is MDS Nordion in Kanata, Ontario, Canada. Their control system design for food irradiators include radiation monitors, restricted openings, and a remote procedure to replace the $Cobalt^{60}$ pencils under water using magnifying lenses and manipulators.

Several hundred different conditions would automatically shut down the system in case of components failures, human errors, or system design inconsistencies.

Thick concrete walls reaching a thickness of 9 3/4 feet surround the irradiation areas.

A multilayered safety system is used, starting from the maze through which the carts are conveyed, to avoid the streaming of radiation around corners. Multiple 90 degrees turns are used to intersect any streaming electrons, x-rays, or gamma radiation.

RISKS AND BENEFITS OF FOOD IRRADIATION

Irradiation is likely to be generally accepted in the future as useful to the public's health as pasteurization of milk is today. Its benefits exceed its risks from a Risk-Benefit analysis perspective. However, there are still lingering questions about some aspects of the new technology.

Irradiation uses electron beams, which could in turn generate x-rays as they interact with matter, or gamma ray sources to irradiate food products. X-rays and gamma rays are short wave length electromagnetic radiation that is not capable, at the energies used, of transmuting nuclei and forming radioactive isotopes in food. Thus they do not increase human exposure to radiation. Once the food has been irradiated, the food pathogens are destroyed, and the radiation does not remain in the irradiated food.

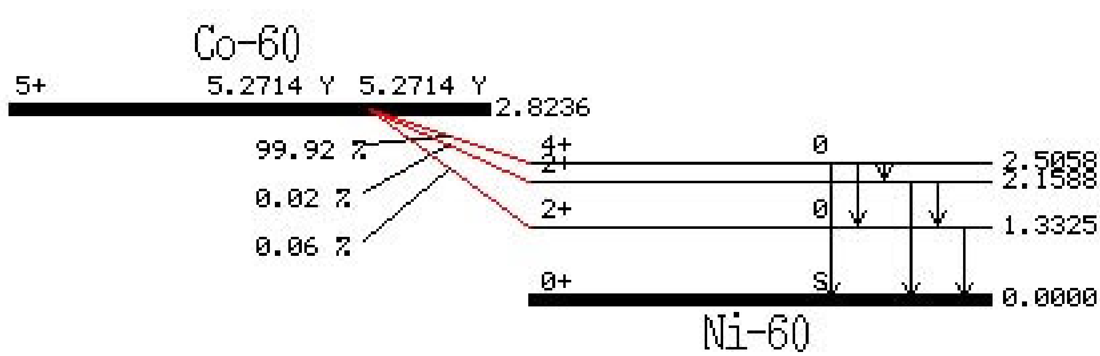

Fig. 7: Decay Scheme of the $Cobalt^{60}$ isotope, showing the energies of gamma rays emission.

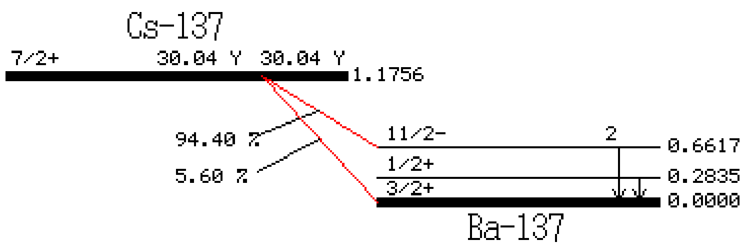

Fig. 8: Decay Scheme of the Cesium^{137} isotope, showing the energies of gamma rays emission.

Gamma ray sources use the Cobalt^{60} or the Cesium^{137} isotopes which are strong gamma ray emitters. The decay scheme for Cobalt^{60} is shown in Fig. 7. The gamma ray energies and their relative intensities or percentage occurrence is shown in Table 3.

Table 3: Gamma ray energies and their relative intensities in Co^{60}, Cs^{137} and Tl^{208}.

Isotope	Gamma ray photons energy keV	Relative Intensity, percent
Co^{60}	346.93	0.0076
	826.28	0.0076
	1173.237	99.9736
	1332.501	99.9856
	2158.77	0.00111
	2505.000	2.0×10^{-6}
Cs^{137}	283.5	5.8×10^{-4}
	661.657	85.1
*Tl^{208}	211.40	0.18
	233.36	0.31
	252.61	0.70
	277.358	6.36
	277.72	-
	485.95	0.050
	510.77	22.8
	583.191	85.2
	587.7	0.04
	650.1	0.036
	705.2	0.022
	722.04	0.203
	748.7	0.043
	763.13	1.83
	821.2	0.040
	860.564	12.53
	883.3	0.031

	927.6	0.132
	982.7	0.205
	1004	0.005
	1093.9	0.40
	1125.7	0.005
	1160.8	0.011
	1185.2	0.017
	1282.8	0.052
	1381.1	0.007
	1647.5	0.002
	1744.0	0.002
	2614.533	100.0

* For absolute intensity multiply by 0.9916

It can be noticed that the maximum gamma ray energy for Co^{60} is:

$$E_{max}^{Co^{60}} = 2.505 \text{ MeV}$$

The decay scheme for Cs^{137} is shown in Fig. 8, its maximum gamma ray energy is lower than that of the Co^{60} isotope:

$$E_{max}^{Cs^{137}} = 0.6617 \text{ MeV}$$

One can consider the interaction by a few high-energy gamma photons through photo-nuclear (γ,n) reactions with some trace elements in the food. For instance one can consider the interaction of energetic gamma photons with $Beryllium^9$ through the reaction:

$$\gamma + {}_4Be^9 \rightarrow {}_0n^1 + {}_2He^4 + {}_2He^{4.} \qquad (4)$$

The threshold energy for this reaction, which is also the binding energy of the neutron in the $Beryllium^9$ nucleus is:

$$E_{th}^{Be^9} = 1.666 \pm 0.002 MeV$$

Neutrons would then activate other elements constituting the rest of the food. However, Beryllium is a toxic metal, and is not expected to be found in the foods being irradiated.

One can also consider the photo disintegration reaction:

$$\gamma + {}_1D^2 \rightarrow {}_0n^1 + {}_1H^1 \qquad (5)$$

The generated neutrons could then activate some other elements in the irradiated food creating some radioactive species. The binding energy of the deuteron is known to be equal to:

$$E_{th}^{D^2} = 2.226 \pm 0.003 MeV$$

The gamma photons from Co^{60} would be able to disintegrate the deuteron nucleus since:

$$E_{max} > E_{th}.$$

However it occurs with a low intensity of $2.0x10^{-6}$ percent.

It is known that the deuteron nucleus possesses the lowest binding energy per nucleon at 1.113 [MeV/nucleon] among the other nuclides, whose binding energy per nucleon averages 8.5 [MeV/nucleon]. The deuterium nucleus occurs in water, as heavy water, at a very low abundance of 150 parts per million (ppm).

NATURAL SOURCES OF GAMMA RAYS

It can be thought that some photonuclear reactions could occur in food, not from the gamma ray sources, but from neutrons originating from natural environmental causes such as cosmic ray showers. Also from energetic gamma rays from natural sources such as $Thallium^{208}$, a member of the $Thorium^{232}$ natural decay chain, which emits gamma rays at an energy above the thresholds for Be^9 and D^2. In fact the maximum photon energy from Tl^{208} is 2.614 MeV above the deuteron binding energy threshold of 2.26 MeV, and it occurs with an intensity of 100 percent.

Since certain foods like Brazil nuts are known to concentrate thorium in their tissue, this matter may be worthy of investigation as a source of activity in foods caused by natural phenomena, rather than by the food irradiation process per se.

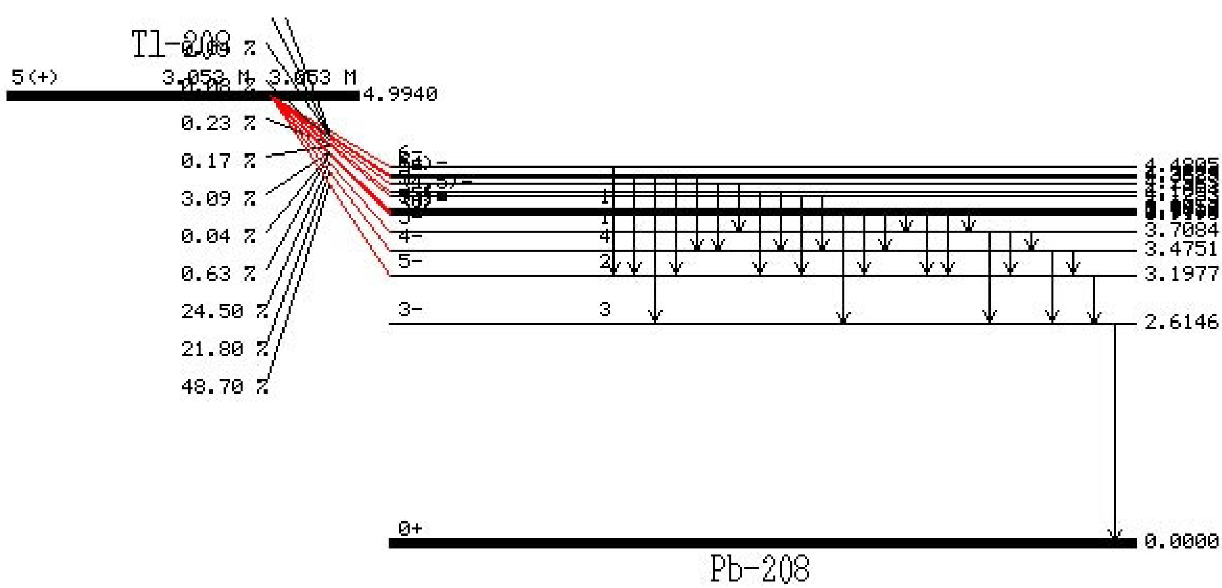

Fig. 9: Gamma rays emissions from the Tl^{208} isotope.

It is a fact that irradiation changes the molecular structure of food. However, it does not produce significant neutron activation products in the process. Like grilling, using microwave ovens, freezing and canning, irradiation can rearrange the molecules of foods but to a degree that it considered as insignificant by scientists. A controversy exists about the creation of unique radiolytic products. For instance, gamma radiation can split the water molecule into ions which are chemically reactive through the reaction:

$$\gamma + H_2O \rightarrow OH^- + H^+ \qquad (6)$$

After decades of studies, toxic substances that are unique to the irradiation process remain to be found.

There are some claims that irradiation contributes to the creation of radioactive waste related to the use of $Cobalt^{60}$ and $Cesium^{137}$ as gamma radiation sources. One should notice that these isotopes decay to nonradioactive isotopes and the isotope filled rods have to be recharged for reuse. This fear is related to a radiological accident caused by the illegal recycling in Mexico and dismantling of some gamma ray Cs^{137} medical radiation sources, which caused inadvertent human exposure.

Some vitamins and nutrients are slightly depleted in the irradiation process, particularly vitamins A, B, C, E and Thiamin. The depletion is of the same order of magnitude as caused by the cooking of foods.

Opposition to the acceptance of food irradiation appears to exist among people opposed to any aspect of the nuclear industry, even though food irradiation is a well studied technology that has been more researched than any food processing technique. Opposition to food irradiation also appears to be a part of the general concern about food safety, where consumers rightly prefer for instance, to have no contaminants added to meat during the handling process, than to have contaminants sterilized by radiation. Irradiation is a complement and not a replacement for proper food handling practices by producers, processors, and consumers.

FUTURE DEVELOPMENTS

Through the process the x-ray conversion, future electron accelerators may be able in the future of producing high energy x-rays by irradiating heavy element targets such as tungsten with electrons. These hard x-rays could have a greater penetration range in materials, overcoming the disadvantage of low penetration of current electron accelerators.

Many products are not taking advantage of the benefits of food irradiation such as fish, shrimp, crabs, etc. Shipboard fish irradiators may be installed in the future on fishing vessels and harbors.

Grain supplies are currently protected against storage insects such as weevils with extremely potent poisonous chemicals, which are mixed with the grain supplies once they are withdrawn from storage, and contaminate, unknown to consumers, the whole food supply system. Bulk and package grain irradiators may in the future dot the grain producing plains as grain elevators now do.

As the process becomes more accepted food preservation through radiation contribution to food safety will eventually reach the same recognition as the sterilization of medical products has in terms of preventing the spread of infectious disease.

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