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NEUTRON MEASUREMENTS *

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INTRODUCTION

Many people are experienced in measuring radiation dose from photons and electrons. These two forms of radiation involve similar measurements since it is secondary electrons produced by the photons which actually deliver the dose. The electron is a light charged particle. Relatively fewer people have experience in measuring neutron dose. The neutron is a heavy uncharged particle. It has nearly the same mass as a proton, i.e. the nucleus of a hydrogen atom. Most of the neutron dose is actually deposited by secondary knock-on protons, but significant fractions come from other heavy particles, secondary electrons and γ-rays.

SOURCES OF NEUTRONS

There are many possible sources of neutrons. Neutrons are produced from electron accelerators above about 10 MeV or from accelerators of heavy particles such as protons and deuterons at lower threshold energies. There are also radioactive sources of neutrons available. Most of these sources are produced by (α, n) reactions on materials such as beryllium, where the α is provided by radioactive elements such as radium, plutonium or americium. There are also some (γ, n) sources, but in these sources the γ-to-neutron ratio is rather large so they are not as desirable and most of them are not used anymore. Another source of neutrons is from isotopes that undergo spontaneous fission, releasing neutrons. ^{252}Cf is the most common of these. From the (α, n) type sources it is quite easy to get neutron sources which emit 10^6 to 10^7 neutrons per second isotropically and much larger sources can be obtained using ^{252}Cf. These neutron sources emit neutrons in the range up to about 10 MeV with the average energy usually in the neighborhood of 4 MeV for the (α, n) sources and slightly above 2 MeV for the ^{252}Cf fission sources. Electron accelerators above 10 MeV produce photoneutron spectra with the highest energy being equal to the energy of the electron minus the binding energy of the neutron in the material that is irradiated.

NEUTRONS IN MEDICINE

There is interest in medicine, both due to beneficial uses and to nonbeneficial production of neutrons. Neutrons have applications in radiotherapy, mostly because the neutron is a high LET radiation; that is, it produces a large amount of ionization per unit path length. High LET radiation is of interest because it is more effective in producing damage in an oxygen deficient tumor than low LET radiation such as photons and electrons. There are many difficulties in using neutrons for radiation therapy. To get a desirable neutron spectrum usually requires an accelerator that is very expensive compared to an electron linear accelerator. It is also bigger, more bulky, and nobody so far has been able to produce a compact unit that can be used for rotation therapy as can the electron accelerators. It is difficult to treat the patients because the depth-dose curve is relatively poor and it is difficult to provide sufficient skin sparing. It is also difficult to produce collimators for a neutron machine. Neutrons are also used in medicine for activation analysis; that is, the patient is subjected to a relatively low neutron dose and then the activation produced in the body is measured by external γ-ray spectroscopy. In this way the concentration of some elements can be determined. Neutron radiography is also possible but has relatively few applications in medicine. The nonbeneficial occurrences of neutrons in medicine are mostly due to the photoneutrons from medical electron linear accelerators and betatrons. The neutrons produce a stray radiation which is uncollimated unlike the beneficial radiation that is being administered to the tumors. This radiation produces a whole-body dose to the patient. These neutrons also cause complications in room shielding. Electron linear accelerators above 10 MeV are now becoming very common in medical physics. Many of the medical physicists have had little training or experience with neutrons and hence this is a relatively unknown field for them.

INTERACTION OF NEUTRONS WITH MATTER

Neutrons interact with matter in many ways. First, there is scattering, both elastic and inelastic. By elastic scattering we mean that type of scattering where all of the energy is accounted for by the kinetic energy of the outgoing particles. Inelastic scattering is that scattering where there is also excitation of the atom which scatters the neutron and this is followed by emissions of γ-rays.

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There are also (n, 2n) reactions where a single neutron interacts with a nucleus and two neutrons emerge from the reaction. Another type of interaction is neutron capture. When a nucleus captures a neutron it is left in an excited state. This excitation energy must be re-emitted, usually but not always, in the form of γ-rays. Neutron capture is usually negligible until the neutron has lost almost all its kinetic energy. When the kinetic energy of a neutron is down to the energy which it would have from collisions with other atoms due to the thermal motion of these atoms, it is called a thermal neutron and has an energy of 0.025 electron volts at room temperature. Most capture is of thermal neutrons and is called thermal-neutron capture. When neutrons interact with the atoms of heavy metals there is a lot of elastic scattering. However, elastic scattering is exactly like a billiard ball collision. Very little energy is transferred to the heavy nucleus so there is almost no energy loss. The large amount of scattering does cause changes of direction and diffusion of the neutrons. Most of the energy loss of neutrons passing through heavy metals is produced by inelastic scattering and (n, 2n) reactions. Every heavy metal has some threshold energy which is the lowest excited state in that nucleus and below which inelastic scattering cannot occur. The (n, 2n) reactions usually have fairly high thresholds of 5 or 6 MeV or more. When all the neutrons are below these thresholds, the only interactions that occur are those due to elastic scattering and there is essentially no further energy loss. Heavy metals become very transparent to neutrons in these energies. With carbon or oxygen such as one finds in tissue there is again both elastic and inelastic scattering. The (n, 2n) reactions are quite unlikely and there are some (n, α) reactions. The nuclei of carbon, hydrogen and oxygen are light enough that there can be a significant amount of energy transferred to the recoiling nucleus.

NEUTRON SHIELDING

In shielding neutrons it is necessary to provide sufficient quantities of material such that the neutron will not only be slowed down and captured, but any secondary radiations due to that capture will be shielded. In the final step of the shielding of neutrons, there is almost always the emission of γ-rays which may be very energetic---up to perhaps 10 MeV---and these must also be shielded. Concrete is one of the most commonly used materials for shielding. It is relatively dense, inexpensive, and contains a fairly large amount of hydrogen which is the most efficient material for removing energy by elastic scattering from neutrons. Most of the neutrons eventually are reduced to thermal energies in concrete and captured either in hydrogen or some of the other elements in the concrete. The neutron capture γ-rays from concrete are quite energetic. The hydrogen produces a 2.2 MeV γ-ray and the other elements produce a whole spectrum of other γ-rays. Sometimes boron is added to concrete. Boron has an extremely high thermal neutron capture cross section and emits a single γ-ray of only 0.48 MeV which is relatively easy to shield against.

Because of the propensity of neutrons for scattering, they penetrate ducts and mazes much more efficiently than γ-rays do. Gamma-rays cannot scatter, for example, through a 90° angle without giving up a large fraction of their energy, while neutrons can elastically scatter through such angles or even larger angles and give up virtually no energy. The shielding of ducts and mazes is a field all by itself.

NEUTRON MEASUREMENT UNITS

In neutron dosimetry one uses many of the same measurement units that are used in γ-ray dosimetry. One can measure, for example, neutron absorbed dose in grays (Gy) where 1 Gy is equal to 1 joule per kilogram of energy absorbed from the neutrons. An older unit is the rad where 100 rads = 1 Gy. One can also measure fluence. The fluence is the number of neutrons per square meter that exist in a given neutron field. Fluence rate (neutrons per m^2 second) is also frequently measured. An especially useful unit for neutrons is the dose equivalent which is measured in sieverts (Sv). The Sv is equal to the absorbed dose in Gy multiplied by a quality factor Q. An older unit for dose equivalent is the rem where 100 rem = 1 Sv. The quality factor is a unit which is intended to account for the increased biological damage from a Gy of neutrons relative to a Gy of x-rays. In this way, one should be able to add dose equivalents due to neutrons and to γ-rays or x-rays and put them all on one scale producing the same biological damage. Since Q is chosen relative to γ-rays or more precisely to x-rays, the quality factor for γ-rays and x-rays is one. Another quantity which is often seen is the relative biological effectiveness or RBE. This is often confused with quality factor. The RBE is the ratio of the biological damage due to neutrons per Gy divided by the biological damage due to x-rays per Gy. The RBE is a measured, or perhaps theoretical quantity, and is reserved for use in radiobiology. The quality factor on the other hand is a legislated quantity and is defined by the various radiation protection organizations. While the quality factor is the same for all biological effects for neutrons of a given energy, the RBE is specified, not only for the energy of the neutrons, but for the particular biological effect in which one is interested; e.g., cancer-induction, cell-killing, or various other biological effects.

MEASUREMENT METHODS

One must detect neutrons through one of the interaction processes described above. Thermal neutrons are the easiest to detect. When they are captured by a nucleus the resulting compound nucleus is highly excited and decays with the emission of energetic heavy-charged particles, e.g., α-rays or γ-rays. This large amount of energy released and the large thermal neutron capture cross sections of some elements, make detection quite easy. For example, in boron 10, a thermal neutron is absorbed with a cross section of 3840 barns and there is an energetic (1.5 or 1.8 MeV) α particle emitted immediately thereafter. Boron tri-fluoride is a gas which can be used to fill proportional counters and the boron may or may not be enriched in boron 10 (the natural abundance of ^{10}B is 20%). The

proportional counters then are quite sensitive to thermal neutrons since the resulting α particle in the gas can easily be measured by the ionization it produces in the proportional counter. A ^3H_e filled proportional counter can be used in a similar manner to a BF_3 counter. Another method of measureing thermal neutrons is by activation. If, after a thermal neutron is absorbed the resulting nucleus is radioactive, then one can measure the radioactivity produced by the neutrons and infer the thermal fluence. Materials which are often used as activation foils in measuring thermal neutrons include, for example, indium and gold. Thermoluminescent dosimeters can also be used to measure thermal neutrons, if one uses something like ^6Li fluoride for the thermoluminescent material. The ^6Li nucleus has a large cross section for thermal neutron absorption emitting about 4.8 MeV in the resulting α and triton particles. This produces a large amount of energy deposition in the thermoluminescent dosimeter.

It is much more difficult to measure fast neutrons. The fast-neutron interactions which result in radioactive daughters have much smaller cross sections (usually less than 1 barn) than the thermal capture processes described previously. This activation can be measured sometimes and these are often called threshold activation detectors, since there is some threshold energy of the neutron which can produce the desired reaction. Threshold activation materials that are often used are copper, phosphorus, and carbon---each with their own threshold and their own energy range of usefulness.

One can also measure fast neutrons by detecting the recoiling target after elastic scattering. For example, one can use proton recoil counters. If the counter has a hydrogenous gas or perhaps a hydrogenous wall, the knock-on protons which are produced by the neutrons can be detected by the counter. A common detector which is often used for personnel dosimetry of neutrons is a film badge, where a nuclear emulsion is exposed to the neutrons, and the neutrons interact with hydrogen in the emulsion to produce recoil protons which leave tracks. These tracks are visible after the film is developed and are counted with the aid of a microscope. The track must have an energy of at least 0.5 MeV in order to be seen and since a neutron can possibly transfer its entire energy in a head-on collision with proton that means that the threshold for detecting neutrons by this method is about 0.5 MeV. So-called etched foil detectors have been finding increasing uses in neutron dosimetry. In the etched-foil detectors, a plastic or crystalline foil is exposed to radiation. The method relies on a particle passing through the foil producing enough damage to the structure that the foil can later be treated with caustic materials such as sodium or potassium hydroxide which preferentially etch away the damaged part. These etch pits can then be counted, either microscopically or by various electronic methods. In detecting neutrons the foils are sometimes covered with a foil of fissionable material and the resulting fission fragments produce the tracks. Some materials are sensitive enough that they can detect a recoil proton passing through the material. In that case, a fission foil is not necessary. Some silicon diodes can be used as neutron detectors, by measuring the forward voltage drop before and after exposure to neutrons. The neutrons collide with the silicon atoms in the crystalline material causing some disorder and increasing the resistance of the diode. These are relatively good detectors and have the advantage of being small and cheap so that many detectors can be used, but they are also very sensitive to electrons since the electron can also cause a recoil of the silicon atoms in the lattice. If there are electrons present above a few MeV it is not advisable to use this method for measuring neutrons.

There is a family of detectors which rely on slowing down the fast neutrons or moderating them until they reach thermal neutron energies and then detecting the resulting thermal neutrons by one of the methods previously described. A common method of doing this is to surround a BF_3 counter with a polyethylene or paraffin moderator and count the thermal neutrons with the BF_3 counter. If the proper thickness of polyethylene or paraffin is chosen one can get a fairly flat response per unit fluence for neutron energies up to several MeV or a little higher. There have been other choices of moderator thicknesses sometimes with the introduction of boron loaded plastics to make the response fairly flat per unit dose equivalent over a wide range of energies. These are usually called remmeters. There have been many attempts to use the moderation of neutrons in the body so that a thermal neutron detector carried as a personnel dosimeter gives a reasonable measurement of neutron fluence, dose, or dose equivalent. These are called albedo dosimeters. Some of these are quite good over limited ranges of neutron energy. They usually suffer from being unable to cover wide ranges of neutron energy and are also sensitive to the direction of the neutrons relative to the body and the dosimeter.

NEUTRON SPECTROSCOPY

In this discussion of the methods of neutron detection, it is necessary to have some reasonable idea of the neutron energy spectrum, and neutron spectrometry is quite difficult. There are several ways of determining neutron spectra. A neutron spectrum can be determined by measuring the angles and energies of the tracks in a nuclear emulsion. This does not work at all below 0.5 MeV and not well below about 1 MeV. It is also very laborious. Another method is to measure thermal neutrons inside a series of hydrogenous spheres of varying diameters. Since the amount of moderation in each of these spheres produces a different response it is possible to make a calculation of the total spectrum by taking all the responses and folding them into a series of equations. This usually requires a computer program, a large number of spheres and a long measurement time. This is called the Multi-sphere or Bonner-sphere method. It is not capable of definition of spectra with any sort of fine structure in it. A similar method uses many different threshold detectors, with the same unfolding requirements and limitations of the multisphere technique. A third method is to use a scintillation spectrometer using a plastic or liquid scintillator. The problem with using scintillation spectrometers is that there are usually a large number of γ-rays present whenever

there are neutrons. The rise time of a pulse from a plastic or liquid scintillation material is different for neutrons and γ-rays and by pulse-shape discrimination it is possible to discriminate against the γ-rays. This method works quite well above 1.5 MeV and can be extended to 1 MeV and perhaps somewhat lower. It is a difficult procedure and it can require a long time to set up a scintillation neutron spectrometer and get it working to the point that you understand what you are measuring. The best measurements of neutron spectra are those measured by time of flight spectrometers where some type of signal is produced at the point the neutron is first created or enters the detection system and the time measured until that neutron gets to a detector some distance away. By knowing how long it takes to travel a given distance one can determine how fast it is going and hence its energy. This again is a difficult measurement and usually requires accelerators and a large expensive array of detectors.

DISCUSSION

The discussion above of possible ways of measuring neutrons may have seemed to emphasize the problems with the different detectors. While it is not my intent to emphasize the difficulties, neutrons are more difficult to measure than photons or electrons. The state of neutron dosimetry and detection is nowhere near as well-defined as that for the light charged particles and photons. There is no universal dosimeter that can be used for example, as there is for measuring γ-rays and x-rays. Compared to γ-rays and x-rays, neutron spectroscopy is extremely difficult. The simplest spectrometer to set up is probably a scintillation spectrometer and it can easily take a man-year or more just to get a scintillation spectrometer operating correctly and to obtain calibration. Calibration itself is quite difficult. The cost of a calibrated neutron source of sufficient strength to use in calibrating the various detectors is many times that of an equivalent γ-ray source. As a result there are relatively few of them around, many of these being at the large national labs. It is possible, however, to get exposures to various neutron spectra at the National Bureau of Standards at a relatively low cost. Every one of the detectors that can be used for measuring neutrons requires some knowledge of the neutron spectrum before one can even choose the detector. This usually must come from theoretical knowledge, Monte Carlo calculations or some empirical estimates of the spectra by detectors which are brought in on a survey basis before you choose the detectors that you will use for dosimetry and precise measurements. The wide range of energies that must be measured also causes greater complications for neutrons than for γ-rays. For example, with a 15 MeV electron accelerator one knows that the maximum energy of the neutrons is about 10 MeV which is quite low. However, one must measure all the way down to thermal neutrons at .025 eV, so we are covering nine orders of magnitude in neutron energy. The γ-rays or x-rays associated with this machine range up to about 15 MeV, but it is known that below, say, 1 kilovolt, the x-rays do not penetrate enough to be a hazard, so one is covering about four orders of magnitude of γ-ray energy. I have not discussed the complications which result when there are high intensities of γ-rays present with the neutrons as is found, for example, if one is trying to measure neutrons inside the room where a 15 MeV medical linear accelerator is operating. This can cause severe problems since all neutron detectors are more or less sensitive to γ-rays. It would be nice to be able to close this talk with a discussion of new developments which promise an end to these difficulties, but while there are many places doing research in neutron measurements and dosimetry none of these on-going projects promise any large breakthroughs. I can only predict that the difficulties of neutron measurements and dosimetry will last for sometime.

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