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Response of semiconductor-type electronic personal dosemeter to high-energy neutrons

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Abstract

In order to improve an active type dosemeter for protection dosimetry against high-energy neutrons, characteristic response of an electronic personal dosemeter consisting of Si semiconductor detector covered with polyethylene radiator has been checked in mono-energetic neutron fields of 14.8 and 65 MeV. Pulse height distributions have been measured for several different radiator thicknesses. An analytical estimation of distributions in energy dissipated in depletion layer of Si detector has been carried out under simplified conditions. A good agreement was confirmed between both distributions in the shape and its variation with the radiator thickness and the neutron energy. The energy dependence of the dosemeter response has also been discussed. It is suggested that the energy dependence could be compensated by introducing the two-window technique with different discrimination levels on the pulse height..

Keywords: Electronic personal dosemeter; Pulse height distribution; Radiator thickness; Energy dependence

1. Introduction

In recent years MW-class proton accelerators have been planned or under construction in the world, which include intense spallation neutron sources, such as NSNS in USA, ESS in EU, J-PARC in Japan, and so on. The radiation dose outside the shielding of the facility is estimated to be dominated by the neutrons up to 100 MeV (Miyamoto et al., 2002). In space activities, experimental or theoretical evaluations have indicated that energetic neurons made a significant contribution to the total personal dose in a space station (Dudkin et al., 1996; Luszik-Bhadra et al., 1999; Bartlett et al., 2003). In addition, the risk associated with cosmic radiation to aircraft crew and frequent flyers has been a matter of concern as occupational exposure (Bartlett, 2004).

With rapid development of neutron sources and fruitful application fields, monitoring of high-energy neutrons becomes more important from a viewpoint of radiation protection. It is well known that the sensitivity of most types of prevailing detectors decreases rapidly with the neutron energy in such a region higher than a few tens of MeV because of decrease in interaction cross sections. A new technique for more effective neutron detection or for compensating a reduction of the sensitivity is expected to be established very soon.

The personal dosemeters for radiation protection dosimetry are classified into two groups: one is used for measuring the total dose integrated over a period, typically one month. A plastic nuclear track detector such as CR-39 is one of most popular elements. A special design of radiator with two-layer structure has been proposed in the previous reports in order to apply to higher energy neutrons up to several tens of MeV (Oda et al., 2003; Oda et al., 2004; Oda et al., 2005).

In this study, our concern is directed to the other dosemeter group of active type that can display the dose rate in real time. We have checked the performance of several types of prevailing detectors including superheated liquid-drop detector (Sawamura et al., 2003). Among them, an electronic personal dosemeter (EPD), composed of a small silicon semiconductor detector and polyethylene radiator, is most promising for practical application to higher energy neutron detection (Luszik-Bhadra, 2007). The main purpose of this study is focused on improvement of EPD response to neutrons with an energy higher than 20 MeV, with understanding the relation with neutron interactions taking place in EPD.

2. Experimentals

In this study, an EPD (NRY21, Fuji Electric Systems, Co. Ltd., Japan) was used, which consists mainly of Si semiconductor detector and a thin polyethylene radiator. The thickness of depletion layer is roughly estimated to be about 50 μm under our operational condition. We modified its original structure in commercial so as to attach a thicker radiator, and adapted in order to pick up the signal, which was lead externally to MCA.

Neutron irradiation experiments were carried out at two facilities; FRS (Fundamental Radiation Sources) and TIARA (Takasaki Ion Accelerator for Advanced Radiation Application),

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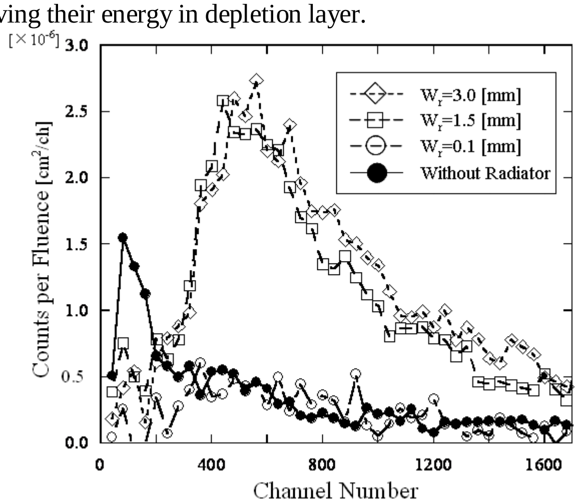
Japan Atomic Energy Agency; (a) neutron field with monochromatic energy of 14.8 MeV, generated by D-T reactions at FRS, and (b) neutron field with broad distribution peaked at 65 MeV at TIARA facility (Baba et al., 1999), generated by bombarding a lithium target with an accelerated proton beam. The EPD was set in each field with CH_2 radiators with several thicknesses of 0.1, 1.5, 3.0 and 4.5 mm.

3. Experimental results

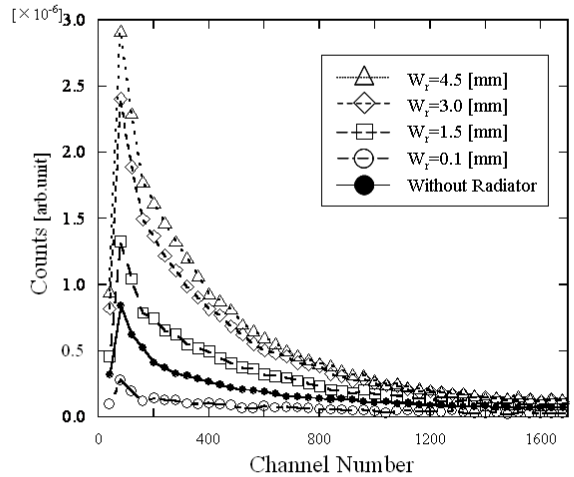
Measured pulse height distributions are shown in Fig. 1. The channel is not calibrated yet, but the channel width and the energy deposited in the depletion layer are estimated to lie in the same order. The neutron fluence could be evaluated in FRS fields, so the ordinate of Fig. 1 (a) is normalized to be the number of signals per unit neutron fluence. On the other hand, it is very difficult to measure accurate fluence in 65-MeV field at TIARA, because the monitors for calibration are sensitive to not only 65-MeV neutrons but also contaminated lower energy ones. This is the reason why the ordinate in Fig. 1 (b) is expressed in arbitrary unit. We estimated a difference from true value in keV would be within a factor 3.

A distribution shown by dots and a solid line, in each case, represents the signal from EPD without radiator, which are attributed to neutron interactions with Si for relatively larger channels and to a considerable amount of accompanying photons for lower channels. Subtracting these components from measured distributions, a contribution of protons recoiled in radiator can be obtained as dotted and broken lines in Fig. 1.

In case of 14.8-MeV neutrons, increase in the number of pulses can be found around 400 to 800 channels. It is shown in Fig. 1 (a) that the radiator effect saturates for radiator thickness of 1.5 mm, according to the maximum range of recoil protons. On the other hand, saturation is not found even at 3.0 mm for 65 MeV neutrons. It is also easily recognized that the average pulse height shifts in the lower side compared with those for 14.8 MeV neutrons. This result is considered to be attributed to a difference in the energy or stopping power of recoil protons leaving their energy in depletion layer.



(a)



(b)

Fig 1. Measured pulse height distribution for different radiator thicknesses; (a) 14.8 MeV, (b) 65 MeV.

4. Analytical calculations of radiator effect

In order to understand well the pulse height distributions obtained experimentally, we try to make a theoretical consideration in an analytical way under some simplified approximations as follows:

1) neutrons are incident normally,
2) no photon is contaminated, for simplicity,
3) air gap between radiator and Si-SSD is neglected,
4) dead layer in silicon is also neglected,
5) depletion layer of Si-SSD is approximated to be 50 μm,
6) attenuation of neutron fluence in radiator is neglected,
7) no reaction with carbon is taken into account.

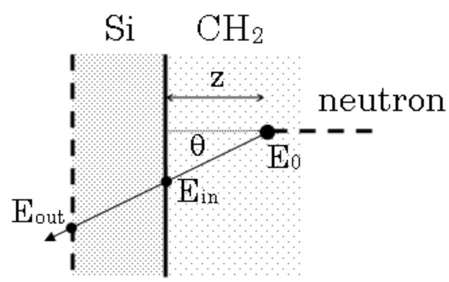


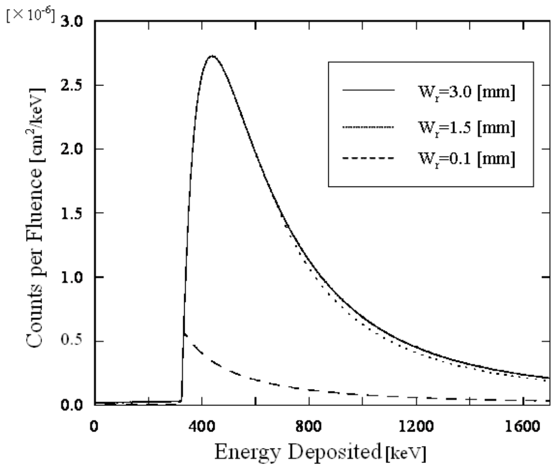
Fig. 2. Geometrical relation in analytical calculation.

Then, the energy deposited, E_d can be calculated by the help of geometry in Fig. 2, where E_d is the difference between the energy, E_{in}, with which a recoil proton enters into the depletion layer, and the energy, E_{out}, with which the proton leaves there. Both energies are evaluated by well-known range-energy relation, $R(E)$. For example, if a proton recoiled in depth, z with an initial energy of E_0 in the direction of θ, then E_{in} is found to be the energy corresponding to the range of $R(E_0)-z/\cos\theta$.

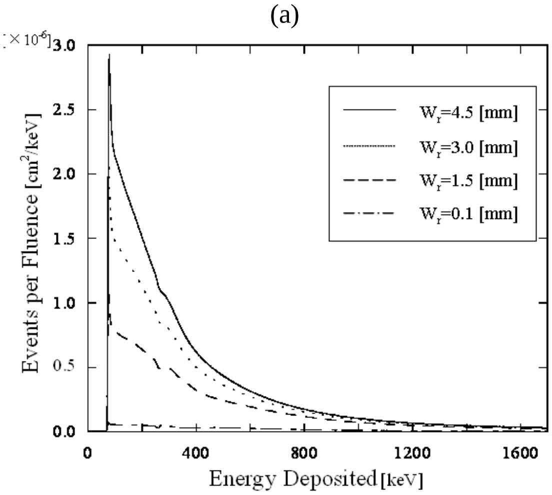
Next, above procedure is adapted to all recoil protons for all positions in radiator with a thickness of W_r and in all directions. Finally, the number of protons is rearranged in terms of the deposited energy as follows:

$$p(E_d) = \frac{d}{dE_d}\int_0^{W_r}\int_0^{4\pi} N\frac{d\sigma}{d\Omega}d\Omega\,dz \qquad (1)$$

Calculation results are shown in Figs. 3 (a) and (b) for 14.8 MeV and 65 MeV neutrons, respectively. An exact energy spectrum has been measured in quasi-monoenergetic neutron field (Baba et al., 1999). So, the spectrum was divided, for simplicity, into a main peak and six lower-energy components, and then we summed up seven pulse height distributions weighted by each relative fraction. The ordinate in both figures is represented as absolute value, the number of protons per unit neutron fluence. There found a fairly good agreement between Fig. 3 and Fig. 1 in the shape of distribution, width of main peak, and variation with radiator thickness.



(a)



(b)

Fig 3. Calculated pulse height distribution for different radiator thicknesses; (a) 14.8 MeV, (b) 65 MeV.

We are now under preparation for introducing a Monte Carlo code, PHITS to obtain more accurate distribution, as well as the contribution of neutron interactions with Si atoms in higher energy region.

5. Dependence of estimated detector response on neutron energy

A successful reproduction of pulse height distributions with acceptable precision mentioned in the previous section will permit us to advance analytical calculations for other neutron energies. The detection efficiency, defined here as the total number of pulses, can be obtained by integrating the distribution shown in Fig. 3 over the deposited energy.

Figure 4 shows the results of calculations, where the detection efficiency is plotted against the neutron energy for five different radiator thicknesses. The efficiency increases with the neutron energy due mainly to longer range of recoil protons. The peak energy depends on the radiator thickness as well as the drop in cross section in a region higher than a few tens of MeV. The calculated result agrees with that obtained by Vareilla et al. (1997) using Monte Carlo calculations within a factor of three in spite of different method, geometry and approximations.

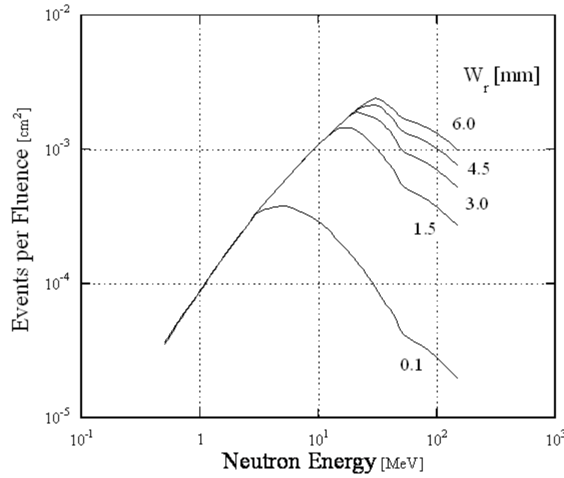


Fig 4. Dependence of detection efficiency, defined as the number of pulses, upon the neutron energy for different radiator thicknesses.

Dividing the efficiency shown in Fig. 4 by the factor for converting the neutron fluence into the personal dose equivalent, *H*p(10) (ICRP, 1996), we can obtain the relative sensitivity or the dosemeter response to the dose equivalent for radiation protection purpose. For example, the response of the dosemeter consisting of Si detector and 3-mm thick radiator is estimated as shown by a solid line in Fig. 5.

Actual neutron fields are often accompanied by a considerable amount of photons, coming directly from radiation sources and indirectly from structure materials through neutron capture interactions. The Si semiconductor detector placed in such a mixed radiation fields will respond to these photons, more exactly to secondary electrons. In general, a certain level is set against the pulse height in order to discriminate such electron components. The absolute value of discrimination level depends on the photon energy, relative abundance of photons in a mixed radiation field, thickness of the depletion layer, the processing electronic circuit, and so on. So, it is assumed in Fig. 5 that the discrimination level is set to be 0.2 MeV, for simplicity.

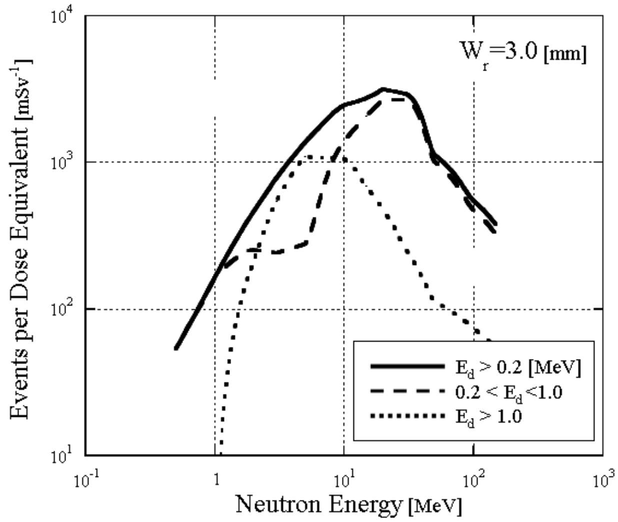


Fig 5. Dependence of relative dosemeter response, obtained by the result shown in Fig. 4 and the conversion factor for the personal dose equivalent. A broken line and a dotted line represent two components corresponding to the number of pulses within respective windows.

An ideal dosemeter should have no energy dependence of its relative response, i.e. the response curve should be a flat straight line. As is recognized in Fig. 5, the designed dosemeter with 3-mm thick radiator is unsuitable for practical application to personal dosemeter for high-energy neutrons. One of possible countermeasures is the two-window method, where additional discrimination level is imposed on the pulse height and operational process such as linear sum of the counts in two windows.

The shape of pulse height distribution observed in Fig. 1 and numerically obtained in Fig. 3 is dependent largely on the neutron energy. The fact implies a possibility that the two-window method may function effectively to compensate large energy dependence. As an example, the pulse height distribution is divided into two components by setting arbitrarily chosen discrimination level of 1 MeV. The variation of two components with the neutron energy is shown by a broken line and a dotted line, respectively in Fig. 5, where a distinct difference is confirmed between two components. It is considered that the energy-response relation may be improved by summing two components weighted by a suitable factor.

The discrimination level of 1.0 MeV is not a best choice, in other words, there must exist an optimum value. We are now trying to find it and to establish a technique for controlling the energy dependence.

6. Conclusion

In this report, characteristic response of a silicon semiconductor detector to neutrons has been investigated both experimentally and theoretically on the purpose of developing an active-type personal dosemeter for high-energy neutrons.

An EPD of commercially available was modified so as to attach a thicker radiator, and adapted in order to pick up the electronic signal, which was lead to MCA. The dosemeter was set in fields of monochromatic 14-MeV neutrons and 65-MeV quasi-monochromatic ones. A difference in the shape of measured pulse height distribution was confirmed between two neutron energies.

In the second step, the pulse height distribution was calculated by an analytical model under simplified conditions. The calculated result could explain the measured distribution well. Then, the dependence of the dosemeter response on the neutron energy was estimated numerically for different radiator thicknesses. Finally, we suggested that a poor energy dependence might be improved by introducing additional discrimination levels on the pulse height.

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