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Design and gamma sensitivity measurement of a novel dual-emitter vacuum Compton detector

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A novel dual-emitter vacuum Compton detector (D-VCD) with higher gamma ray detecting efficiency is proposed. The emitters are made of Ta–Al clad metal. The gamma ray sensitivity is studied by Monte Carlo simulation using the MCNP code. A comparison between calculations and results measured by using the 1.25 MeV gamma ray of Co-60 is also performed. Experimental sensitivities for two sample D-VCDs with the same materials and structures are 1.92×10^{-20} and 2.02×10^{-20} C$\cdot$cm^2/MeV separately, which are consistent with the simulation result of 1.98×10^{-20} C$\cdot$cm^2/MeV and are 4 times higher than that of VCD with a single Fe emitter. According to the simulation results, in a gamma energy range from 0.5 to 3 MeV, the maximum sensitivity variance for the D-VCD is less than 15%, and less than 5% in a range from 1 to 2 MeV in particular. The novel D-VCD is applicable to the detection of intense pulse gamma rays.

Keywords: vacuum Compton detector, sensitivity, pulsed gamma ray

PACC: 0785

1. Introduction

In the field of intense pulsed gamma ray detection and diagnostics, two types of current-mode detectors are often used to measure the intensity and the variation of radiation. One type is scintillation-photoelectric detector. The gamma ray deposits part of its energy in the scintillator, then the deposited energy is transferred to photons. These photons can be measured by photoelectric devices such as a photo multiplier tube (PMT). The sensitivities for these scintillation detectors range from 2.5×10^{-11} to 1.0×10^{-19} C$\cdot$cm^2/MeV.[1] The upper measuring limits for these detectors are determined by the hardness of the scintillator and the linearity of the devices. Another type of current-mode detector is called a charge-collecting detector. A Compton detector is a charge-collecting detector. It is often used for intense pulse gamma ray measurement. When a gamma ray passes through the detector and interacts with the emitter metal, plenty of electrons are ejected from the emitter surface and the net charges of the emitter can be measured.[1,2]

A vacuum Compton detector (VCD), which has the merits of large dynamic linearity range and simple structure, is suitable for intense pulse ray detection.[1] Ebert and Lauzon,[3] Hsu and Lee[4] and Davis[5,6] designed a VCD with a single emitter and thin incident window structure for high-bandwidth (∼GHz) measurements, the gamma ray sensitivities could range from 4.9×10^{-21} to 1.1×10^{-20} C/MeV. For the thin incident window design, the effect of the electrons that are generated from the window can be reduced as little as possible. However, it is difficult to maintain a static vacuum for a long time. May *et al*[1] introduced a VCD with a thick incident window for low-bandwidth measurements, and the sensitivity could reach a range of 7.9×10^{-21} to 1.4×10^{-20} C$\cdot$cm^2/MeV. The sensitivities for the VCDs described above were both less than 1.5×10^{-20} C$\cdot$cm^2/MeV. So it is necessary to develop a new type of VCD with higher sensitivity.

In the present paper, a novel dual-emitter VCD (D-VCD) with a thick incident window and a high sensitivity of 2×10^{-20} C$\cdot$cm^2/MeV is described. The D-VCD can be well processed and the static vacuum can be maintained for a long time. For an energy range of 0.5 to 3 MeV, the maximum sensitivity variance is less than 15 per cent. It will be applicable to the measurement of intense pulse bremsstrahlung radiation from electron accelerators and fission gamma rays.

2. Structure of the D-VCD

The D-VCD is composed of a radiation incident window, an exit window, a cylinder airproofed wall and two emitters (gamma-electron converter targets). The emitters are made of two metals. The static vacuum of the system is less than 10^{-2} Pa. The schematic is shown in Fig.1.

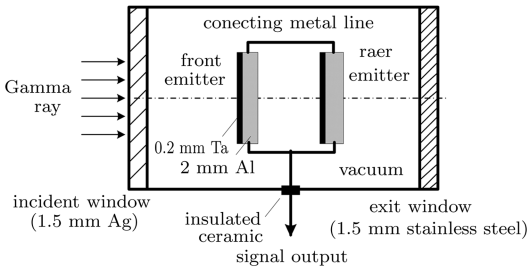


Fig.1. Schematic of D-VCD structure.

A collimated parallel beam of gamma rays passes through the D-VCD, and plenty of electrons will be produced from the incident window, exit window and the emitters by photoelectric effects, the Compton effect and the pairs effect. The sensitivity is mainly contributed by the emitters. By measuring the net charges or the current of the emitters, the intensity of the gamma ray can be measured.

When a gamma ray interacts with materials, the number of ejected electrons from the surface is related to the atomic number and the thickness of the materials. Using the Monte Carlo code MCNP 5,[7] the relationship between the electron-ejecting ability and the material thickness for different metals is shown in Fig.2.

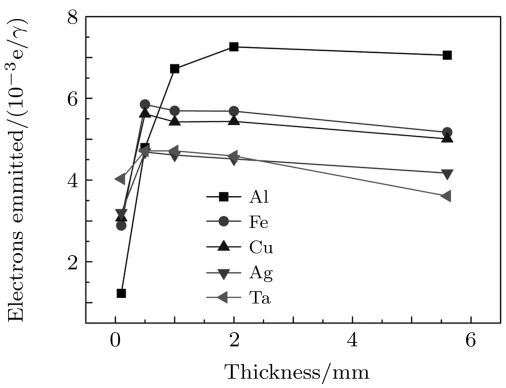


Fig.2. Forward-ejecting electron ability variation with thickness.

Figure 2 shows that for most materials, when the thickness is less than 0.5 mm, the electrons ejected from high Z (Z is the atomic number) materials are more numerous than those from low Z materials, and the electron number varies rapidly with thickness. However, when the thickness is larger than 0.5 mm, the electron emission ability of high Z materials becomes saturated and is obviously less than that of low Z materials. In a thickness range of 1 to 6 mm, silver (Ag) material ejects far fewer electrons than other metals. On the other hand, for maintaining a vacuum for a long time, the thickness of the incident window should be larger than 1 mm. If we choose silver material with a thickness of about 1.5 mm as the incident window, the number of ejected electrons can be reduced by approximately 40% compared to aluminium material with the same thickness.

In D-VCD a thick silver material is used as the incident window. There are three methods to reduce the effect of the electrons ejected from the window. The first method is to set a sweeping magnet between the window and the emitter, so that the electrons can be swept out by the magnet and cannot reach the emitter. Second, according to the angular distribution of the electrons, the distance between the window and the emitter can be increased in order to reduce the solid angle subtended by the emitter; in this way the number of electrons reaching the emitter can be reduced. The third method is to improve the structure of the emitter, increasing the number of back-ejecting and back-scattering electrons by the emitter. In the D-VCD a pair of electron emitters is used. The base plates of the emitter are of aluminium with a thickness of 2 mm, and high-Z material is combined on the other side; this combination structure will emit more electrons from both sides of the emitter. Figure 3 shows the back-ejecting ability for several materials with different thicknesses.

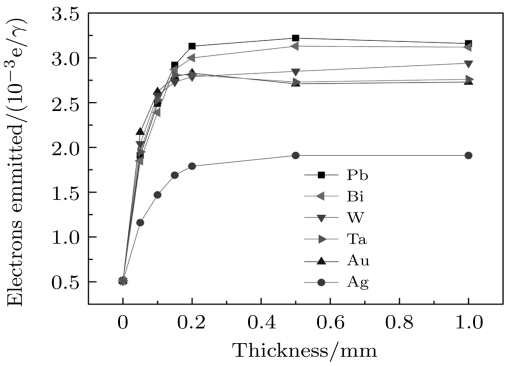


Fig.3. Numbers of back-ejecting electrons for several materials.

3. Gamma ray sensitivity and energy response

Supposing that the energy of an incident gamma ray is E(MeV), the flux density is ϕ (γ/cm^2), the effective irradiation area of the emitter is $A(\mathrm{cm}^2)$, and the net charge quantity of the emitter is Q(C), then the intrinsic sensitivity of D-VCD is calculated to be $S(E) = Q/(E\phi A)$.

When the diameter of the collimator is smaller than that of the emitter, the electrons which are produced from the cylinder metal wall can be ignored. The net charge quantity of the emitter is determined by the forward and back ejecting electrons from the incident window, the emitter and the exit window. The numbers of electrons entering into and departing from the dual emitters are shown in Table 1, obtained by using the photon–electron combined transport MCNP 5[7] code.

Table 1. Numbers of electrons entering into and departing from the dual emitters.

emitter	side	number of ejecting electrons	number of injecting electrons
emitter 1	left	e11: 2.65 $\times 10^{-3}$	e12: 2.10 $\times 10^{-3}$
	right	e13: 6.946 $\times 10^{-3}$	e14: 1.035 $\times 10^{-3}$
emitter2	left	e21: 3.084 $\times 10^{-3}$	e22: 3.044 $\times 10^{-3}$
	right	e23: 6.533 $\times 10^{-3}$	e24: 6.63 $\times 10^{-4}$

From Table 1, the net charge quantity of the dual emitters can be calculated to be

$$\begin{aligned} Q &= (\mathrm{e11} - \mathrm{e12} + \mathrm{e13} - \mathrm{e14}) \\ &\quad + (\mathrm{e21} - \mathrm{e22} + \mathrm{e23} - \mathrm{e24}) \\ &= 1.237 \times 10^{-2}\mathrm{e} \end{aligned}$$

for one incident gamma ray on average. The diameter of the emitter is 5 cm. So the intrinsic sensitivity for D-VCD is 1.98×10^{-20} C $\cdot$ cm^2/MeV.

Because the cross section of generating electrons depends on the gamma energy, the sensitivity is dependent on gamma energy (i.e. energy response). For the fission gamma ray, the energies range from 0.2 to 14 MeV and mainly range from 0.5 to 3 MeV; the average energy is about 1.2 MeV. Figures 4 and 5 show energy response curves for the D-VCD, which are also calculated by using the MCNP 5 code.

It can be concluded that the maximum sensitivity variance is less than 15% in a range from 0.5 to 3 MeV and less than 5% in a range from 1 to 2 MeV.

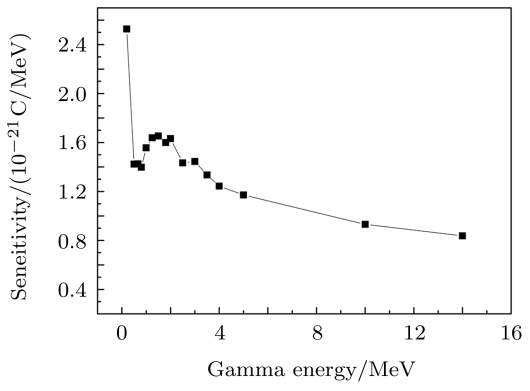


Fig.4. Gamma sensitivity in a range from 0.2 to 14 MeV.

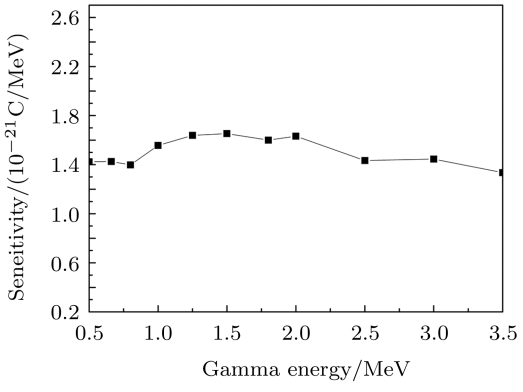


Fig.5. Gamma sensitivity in a range from 0.5 to 3 MeV.

4. Sensitivity experiment results and conclusion

In order to compare with the simulation results, an experiment is carried out for two sample D-VCDs using a Co-60 source in the Northwest Institute of Nuclear Technology. Co-60 emits gamma rays with energies of 1.17 MeV and 1.33 MeV separately with almost the same emission probability which is very close to unity. It can be regarded as a single valued energy source which emits gamma rays at an average energy of 1.25 MeV. A lead collimator with a diameter of 40 mm and a length of 200 mm is used, and the distance between the end of the collimator and the incident window of the D-VCD is 94 cm. The gamma exposure rate is measured by an ionization chamber and UNIDOS dosemeter, and the output current is transferred by a low-noise cable and measured by an amperemeter. The experimental layout is shown in Fig.6.

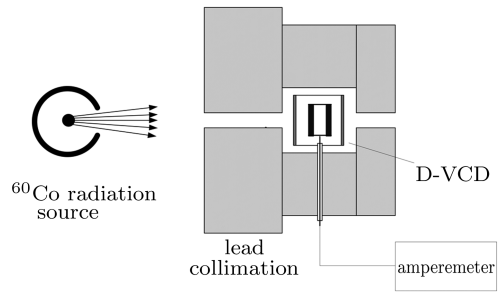


Fig.6. Layout of sensitivity experiment.

The experimental results of the two sample D-VCDs with the same materials and structures are listed in Table 2.

Table 2. Results of sensitivity experiment.

detector	dark current/pA	signal current/pA
D-VCD-1	–0.20	58.0
D-VCD-2	–0.65	60.7

The gamma exposure rate on the surface of the incident window is measured to be 89.1 R/min, so the gamma energy flux is calculated to be 3.02×10^{9} MeV/(cm$^2\cdot$s). From Table 2, the sensitivities of the D-VCDs are $1.92\times10^{-20}$and 2.02×10^{-20} C$\cdot$cm^2/MeV separately which are consistent with the simulation result, 1.98×10^{-20} C$\cdot$cm^2/MeV.

Owing to the dual-emitter structure design, the gamma sensitivity of D-VCD can be larger than 1.9×10^{-20} C$\cdot$cm^2/MeV. On the other hand, using the thick incident window, the D-VCD can be well processed and the static vacuum can be maintained for a long time. The linear output current of the VCD can be more than 100 A, so the detector can be used to measure an intense pulse gamma ray with intensities ranging from 10^{18} to 10^{23} MeV/(cm$^2\cdot$s). When the gamma energies range from 0.5 to 3 MeV, the uncertainty of energy-flux measurements by using the D-VCD will be less than 15% because the energy response is relatively flat.

Acknowledgement

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