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Photon interaction with semiconductor and scintillation detectors

V. P. Singh[1] · N. M. Badiger[1]

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Abstract Mass attenuation coefficients, effective atomic numbers, and electron densities for semiconductor and scintillation detectors have been calculated in the photon energy range 1 keV–100 GeV. These interaction parameters have been found to vary with detector composition and the photon energy. The variation in the parameters with energy is shown graphically for all the partial photon interaction processes. The effective atomic numbers of the detector were compared with the ZXCOM program, and the results were found to be comparable. Efficiencies of semiconductor and scintillation detectors are presented in terms of effective atomic numbers. The study should be useful for comparing the detector performance in terms of gamma spectroscopy, radiation sensitivity, radiation measurement, and radiation damage. The results of the present investigation should stimulate research work for gamma spectroscopy and radiation measuring materials.

Keywords Semiconductor · Scintillation · Attenuation coefficients · Z_{eff}

1 Introduction

Radiation interaction with elements, compounds, and composite materials has become a thrust area of research and development to investigate material properties and their various applications. The process of radiation interaction is being used for various applications in nuclear physics, radiation physics, radiation detection, radiobiology, medicine, agriculture, and industry. The mass attenuation coefficients, effective atomic numbers, and effective electron densities are basic quantities required to study the photon interactions. The interaction depends on incident photon energy and elements of the absorbing material (i.e., atomic number). In a compound or composite material (e.g., concrete, polymer, alloy, biological material), the atomic number is represented by an effective atomic number analogous to the atomic number of a single element. The effective atomic number varies with photon energy, whereas the atomic number of an element is constant for all photon energies.

Semiconductors and scintillation detectors are widely used for X- and gamma-ray measurements. These detectors are utilized in different fields of science and technology, mainly for identification of gamma-ray emitters and sometimes only for radiation detection. The sensitivity for gamma-ray detection is essential for the identification of radiation and different isotopes. Scintillation detectors have a much greater efficiency for interactions with gamma-rays compared to gas- and liquid-filled detectors. Semiconductor-based detectors have shown better energy resolution and good stability over time, temperature, and operating parameters. The instruments consist of scintillation and semiconductor detectors to provide the measure of the energy of a radiation interaction and the type of radionuclide. The scintillation and semiconductor-based detectors are being used in nuclear physics laboratories, research reactors, nuclear power plants, and accelerators. These detectors are being utilized in laboratories and industries for gamma-ray detection in online and off-line

✉ V. P. Singh
kudphyvps@rediffmail.com

[1] Department of Physics, Karnatak University, Dharwad 580003, India

measurements based on the requirements and characteristic suitability.

The mechanisms for measurement of the energy of the photon and the type of radionuclide require detailed information about the interaction with an element or a compound. The interaction probability (scattered/absorbed) per unit length of a photon with an atom is described by the mass attenuation coefficient (fundamental interaction parameter). The mass attenuation coefficient is utilized for the calculation of the effective atomic number and the effective electron density of a compound or composite material. Therefore, knowledge of the mass attenuation coefficient, effective atomic number, and effective electron density is essential in comparing the detector efficiency and resolution.

Studies on effective atomic numbers and electron densities have been reported by several investigators for chemical compounds [1, 2], low-Z materials [3, 4], alloys and steels [5–8], glass and minerals [9–12], biological materials [13], detectors [14, 15], tissue substitutes [16–18], and composites [19].

There are some studies which calculate the effective atomic numbers of semiconductors [20–22] in the literature. The radiation damage to some widely used semiconductor materials has been simulated using FLUKA [23]. This has encouraged us to calculate the effective atomic numbers and electron densities, which should be directly applicable to gamma spectroscopy, radiation sensitivity, radiation measurement, and radiation damage.

2 Computational method and theoretical background

The mass attenuation coefficients of a compound or composite material are determined by the transmission method using Lambert–Beer's law ($I = I_0 e^{-\mu_m t}$), where I_0 and I are the incident and attenuated photon intensity with energy E, respectively, $\mu_m = \mu/\rho$ (cm^2 g^{-1}) is the mass attenuation coefficient, and t(g/cm^2) is the mass thickness of the medium (the mass per unit area). The total μ_m value for materials composed of multi elements is the sum of the $(\mu_m)i$ values of each constituent element obtained by the following mixture rule ($\mu_m = \sum_i^n w_i (\mu/\rho)_i$), where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the ith element using the WinXcom program [24], which was updated for XCOM programs [25]. The quantity w_i is given by $w_i = n_i A_i / \sum_j^n n_j A_j$ with the condition $\sum_i^n w_i = 1$, where A_i is the atomic weight of the ith element and n_i is the number of formula units.

The total atomic cross sections (σ_t) for a compound or composite material can be obtained from the μ_m values using the following relation [26];

$$\sigma_t = \frac{\mu_m M}{N_A}, \tag{1}$$

where $M = \sum_i^n n_i A_i$ is the molecular weight of a compound or composite material and N_A is Avogadro's number. The effective atomic cross section (σ_a) can be calculated by the following equation:

$$\sigma_a = \frac{1}{N_A} \sum f_i A_i \left(\frac{\mu}{\rho}\right)_i. \tag{2}$$

Total electronic cross section (σ_e) for a compound or composite material is calculated using the following equation [12]:

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i = \frac{\sigma_a}{Z_{eff}}, \tag{3}$$

where $f_i = \frac{n_i}{\sum_i n_i}$ denotes the fractional abundance of the element i with respect to the number of atoms, such that $\sum_i^n f_i = 1$ and Z_i is the atomic number of the ith element. σ_a and σ_e are related to the effective atomic number (Z_{eff}) of a compound or composite material through the following relation [12];

$$Z_{\text{eff}} = \frac{\sigma_a}{\sigma_e}. \tag{4}$$

The effective electron density, N_{el} (number of electrons per unit mass) of a compound or composite material is derived from following relation:

$$N_{el} = \frac{\left(\frac{\mu}{\rho}\right)}{\sigma_e} = \left(\frac{Z_{eff}}{M}\right) N_A \sum_i n_i \tag{5}$$

Recently, a program, direct-Z_{eff}, has been developed for the calculation of mass attenuation coefficients, effective atomic numbers, and effective electron densities for a compound or composite material for photon energies of 1 keV to 100 GeV [27]. In the present investigation, the direct-Z_{eff} program was used to calculate mass attenuation coefficients, effective atomic numbers, and effective electron densities of semiconductor and scintillation detectors.

3 Results and discussion

The most popular semiconductor and scintillation detectors were chosen in the present investigation. By using their chemical compositions, the mass attenuation coefficients (μ/ρ), effective atomic numbers (Z_{eff}), and effective electron densities (N_{el}) were calculated in the photon energy range of 1 keV to 100 GeV. In the following subsections, energy and chemical composition dependencies of the μ/ρ, Z_{eff}, and N_{el} for total and partial interaction are discussed.

3.1 Total (with coherent) photon interaction

The total mass attenuation coefficients, μ/ρ, of the semiconductor and scintillation detectors in the photon energy range of 1 keV to 100 GeV are shown in Fig. 1. The variations in the μ/ρ are due to the chemical composition and energy dependency. In the low-energy region, μ/ρ have the highest values, where the photoelectric effect is dominant and the interaction cross section is proportional to $Z^{4-5}/E^{3.5}$. In the intermediate energy region, the incoherent scattering is the dominant interaction process. There

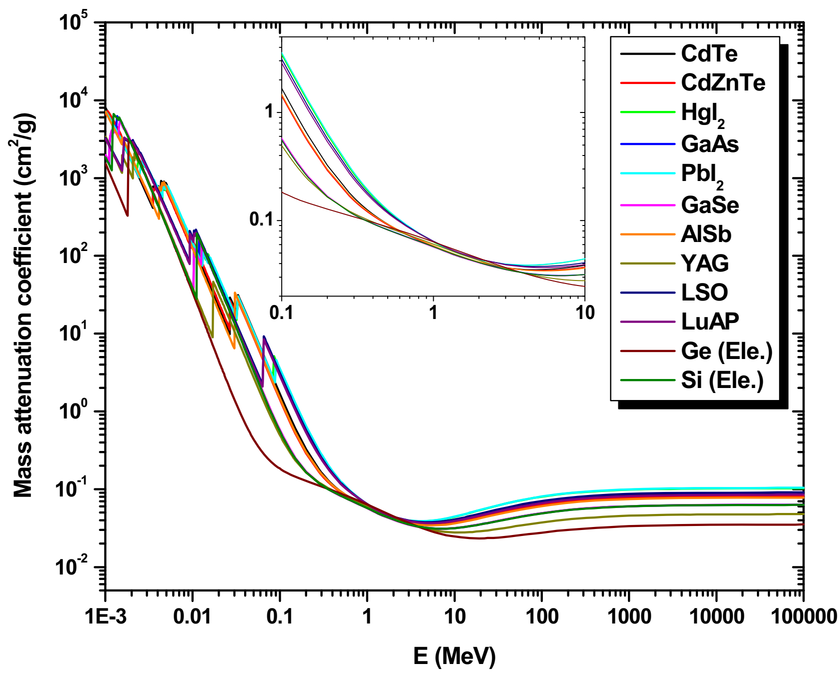

Fig. 1 Mass attenuation coefficients of semiconductor and scintillation detectors

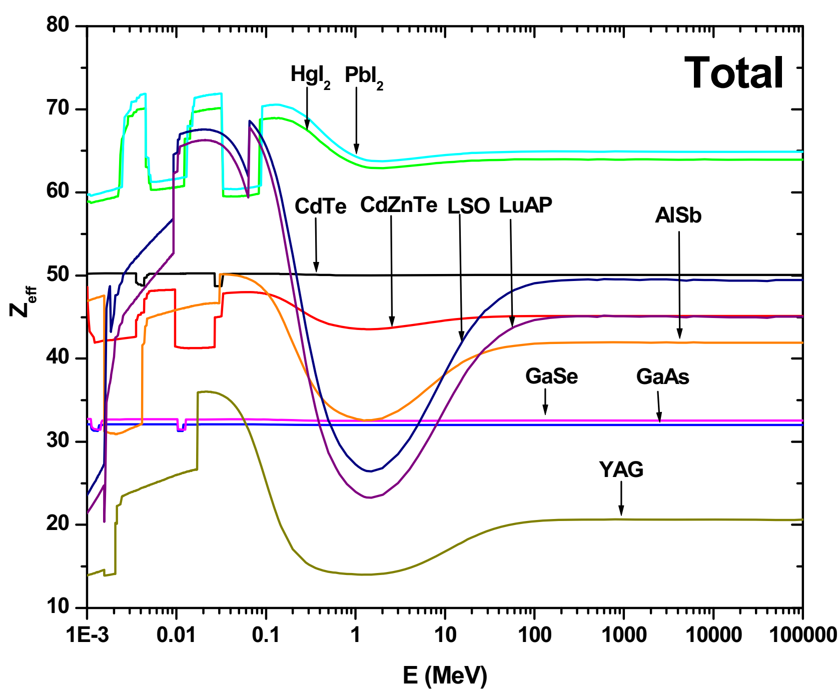

Fig. 2 Effective atomic numbers (total) of semiconductor and scintillation detectors

is a linear Z-dependence of incoherent scattering, and the μ/ρ are found to be constant. In the high-energy region, μ/ρ increase, where the pair production is dominant and the interaction cross section is proportional to Z^2.

For the total photon interaction process, the variations in Z_{eff} and N_{el} with photon energies are shown in Figs. 2 and 3, respectively. From Fig. 2, it is clear Z_{eff} increases with energy initially and then decreases up to 2 MeV (approx.), however some cases there is insignificant change and some cases multiple peaks are observed. Above 100 MeV, Z_{eff} remains almost constant for all the detectors. This is due to the dominance of pair production in the high-energy region. In Fig. 3, the variations in N_{el} with photon energy for the total interaction processes are similar to that of Z_{eff} and can be explained similarly.

From Fig. 2, it is observed that the variation in Z_{eff} depends upon the chemical compositions of the detectors. The PbI_2 detectors contain a larger Z (Pb) value than any of

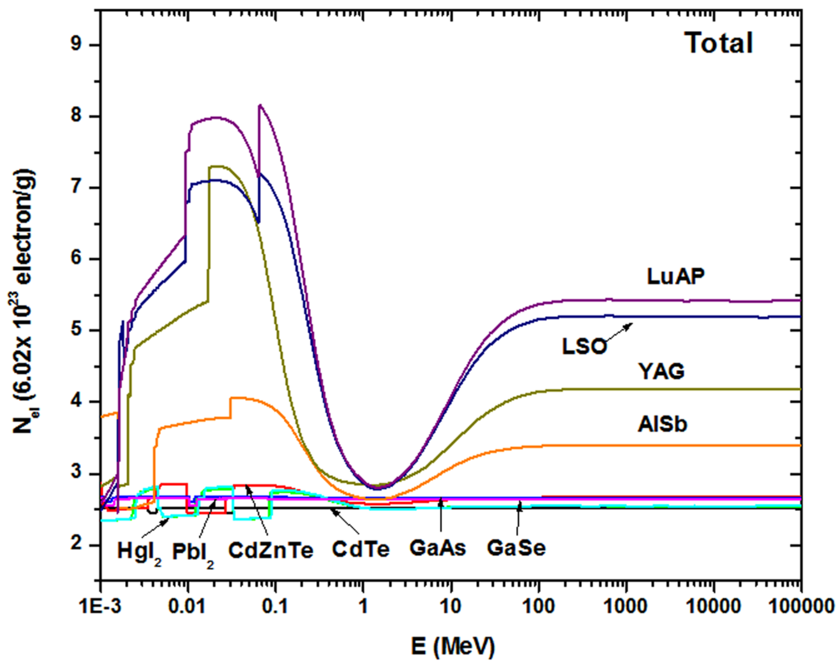

Fig. 3 Effective electron densities (total) of semiconductor and scintillation detectors

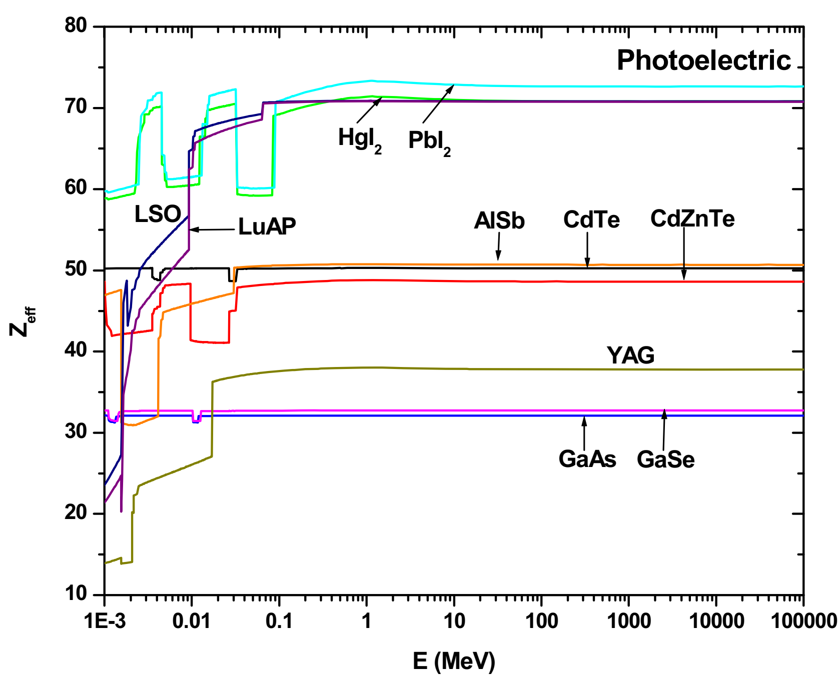

Fig. 4 Effective atomic numbers (photoelectric) of semiconductor and scintillation detectors

the other detectors due to which the largest Z_{eff} to be observed. The LSO and LuAP detectors show a sharp jump in Z_{eff} with energy due to the composition of the low- and high-Z elements.

The variation in Z_{eff} for total interaction reflects the importance of the partial photon interaction processes. The dominating photon interaction process is the photoelectric absorption at low energies, incoherent (Compton) scattering at intermediate energies, and pair production at high energies. Coherent (Rayleigh) scattering does not play any significant role, since it occurs mainly at low energies, where the photoelectric effect is the most important interaction process.

At a low-energy range ($E < 0.01$ MeV), the maximum Z_{eff} is found where the Z^{4-5} dependence of the interaction cross section for the photoelectric effect contributes to the highest-Z of the detector. At the intermediate energy range (0.05 MeV $< E < 5$ MeV), Compton scattering is the

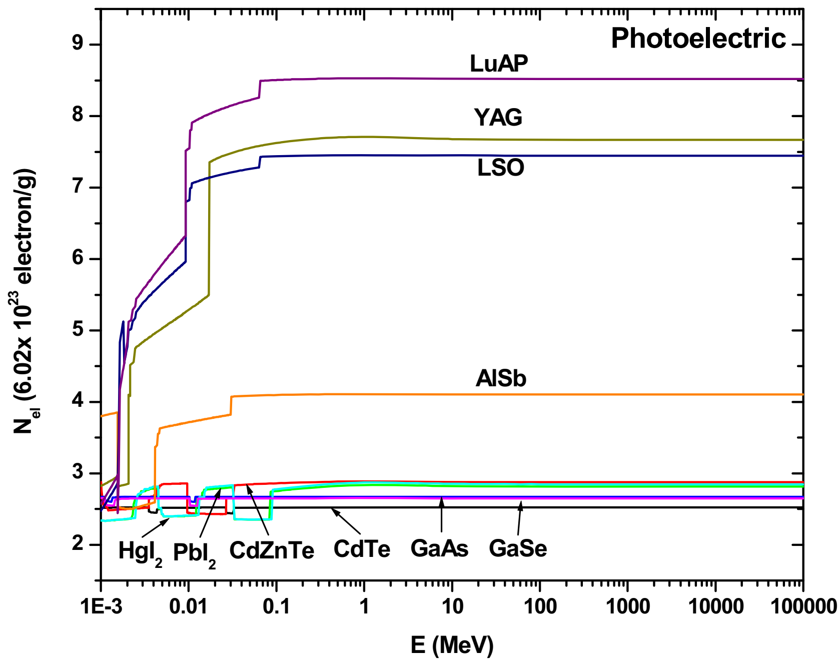

Fig. 5 Effective electron densities (photoelectric) of semiconductor and scintillation detectors

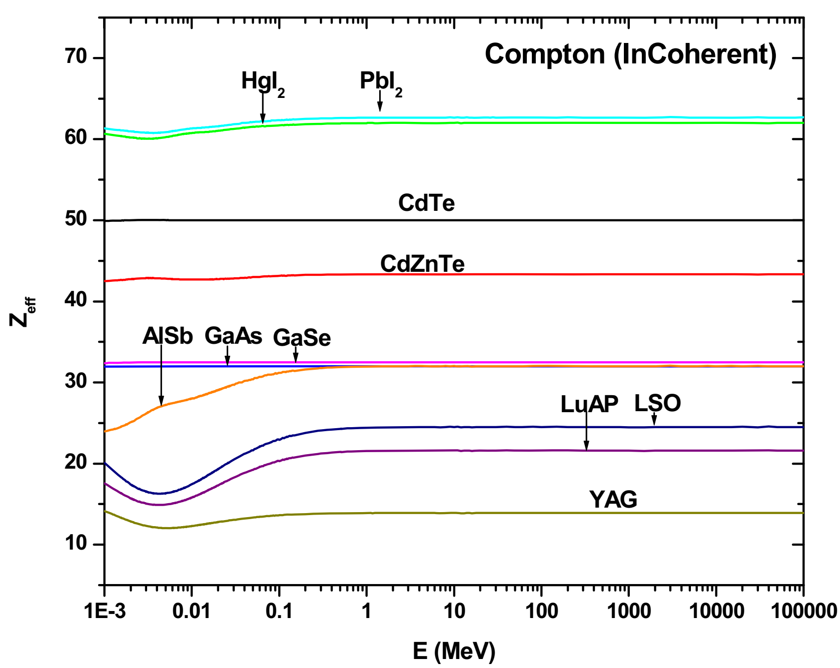

Fig. 6 Effective atomic numbers (incoherent) of semiconductor and scintillation detectors

main photon interaction process. At high energies (typically $E > 100$ MeV), Z_{eff} becomes constant again, but smaller than in the low-energy range. This is due to the dominance of pair production. Hence, pair production provides less of a contribution to the higher-Z elements than the photoelectric effect. It is to be noted that the effective atomic numbers of the detectors are found to be constant in the pair production region ($E > 100$ MeV).

The largest Z_{eff} value among the selected semiconductor and scintillation detectors was observed for PbI_2, followed by HgI_2. The values of Z_{eff} show that the interaction probability of the photon with the detectors is the largest, whereas it is the lowest for YAG. The largest interaction probability of the photon with the PbI_2 provides the highest efficiency of the detector. Therefore, the efficiency of semiconductor and scintillation detectors are presented in

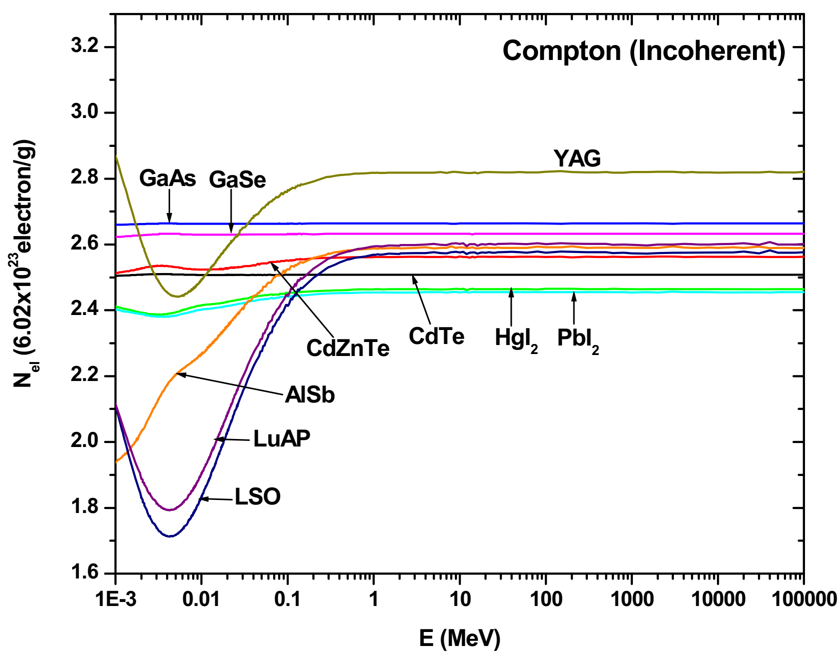

Fig. 7 Effective electron densities (incoherent) of semiconductor and scintillation detectors

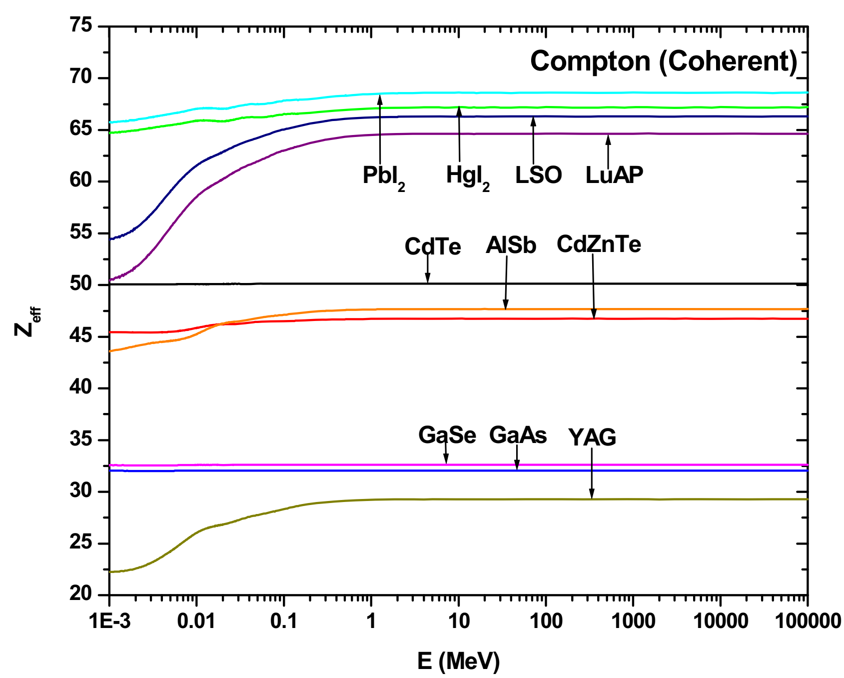

Fig. 8 Effective atomic numbers (coherent) of semiconductor and scintillation detectors

terms of effective atomic numbers. However, the PbI_2 is not a suitable detector because the electron–hole pair creation requires an energy value of 7.68 eV, which is very large compared to 2.96 eV for the Ge detector [28]. During the selection of a suitable detector, photon interaction characteristics should be compared for each parameter in order to get the desired results.

3.2 Photoelectric absorption

For the photoelectric absorption process, the variations in Z_{eff} and N_{el} with photon energy are shown in Figs. 4 and 5, respectively. Figure 4 shows the most significant variations in Z_{eff} are due to the chemical compositions of the detectors. Below 10 keV, the variations in Z_{eff} are more

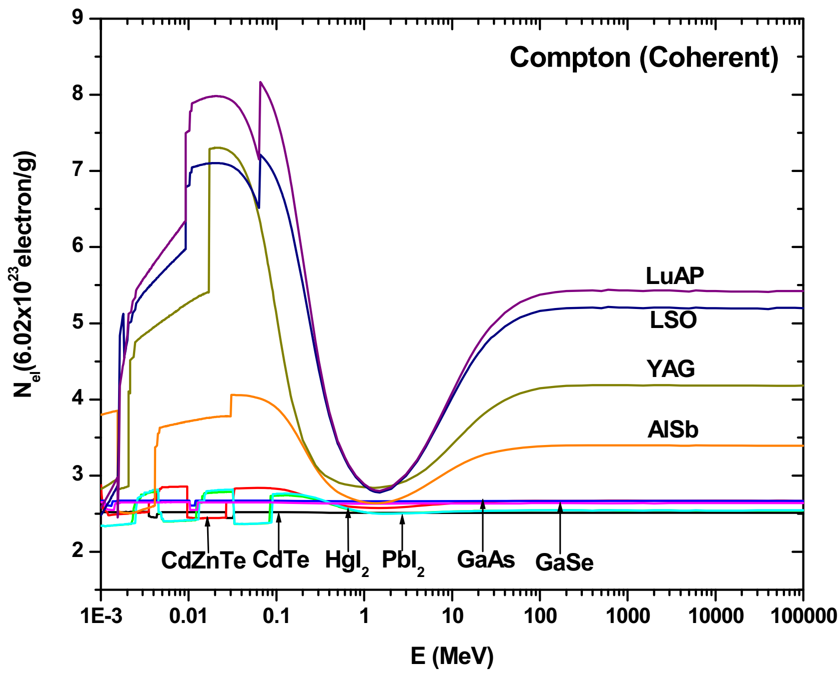

Fig. 9 Effective electron densities (coherent) of semiconductor and scintillation detectors

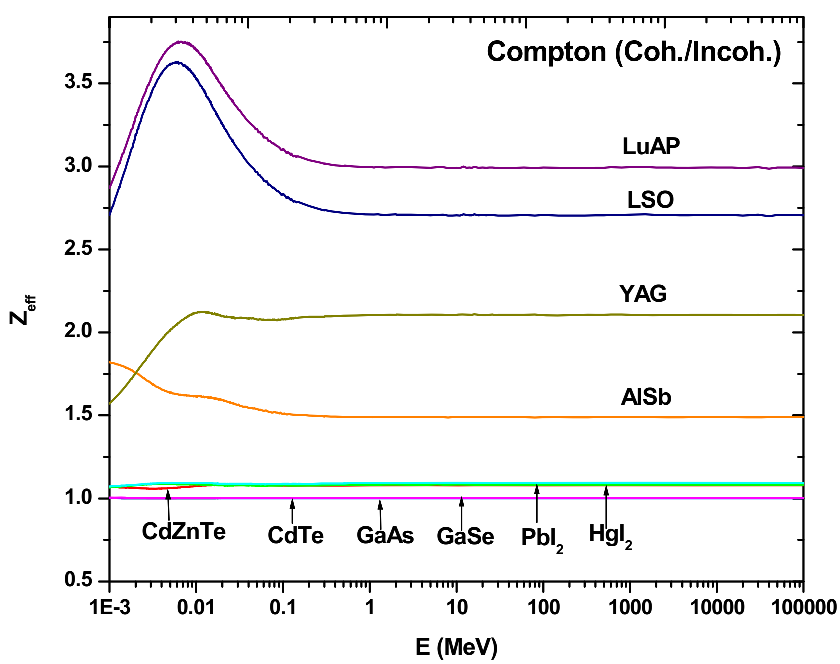

Fig. 10 Effective atomic numbers (coherent/incoherent) of semiconductor and scintillation detectors

pronounced in the detectors containing high-Z elements, and there is no variation in the CdTe, GaAs, and GaSe detectors, except for a few energies. The sensitivity of these detectors is low; however, the behaviors of Z_{eff} for all detectors are similar after 100 MeV. The variation in N_{el} for photoelectric absorption shown in Fig. 5 can be explained similarly to Fig. 4.

3.3 Incoherent (Compton) scattering

For incoherent scattering, the variations in Z_{eff} and N_{el} with photon energy are shown in Figs. 6 and 7, respectively. From Fig. 6, it is found that Z_{eff} increases sharply with an increase in the energy region 1–500 keV. Beyond 1 MeV, Z_{eff} is independent of photon energy for all the

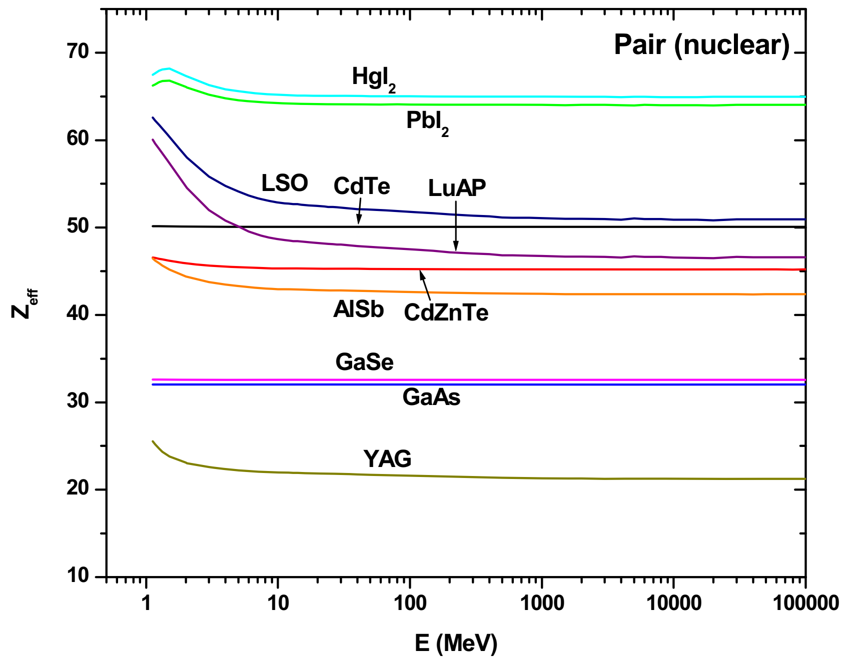

Fig. 11 Effective atomic numbers (nuclear pair) of semiconductor and scintillation detectors

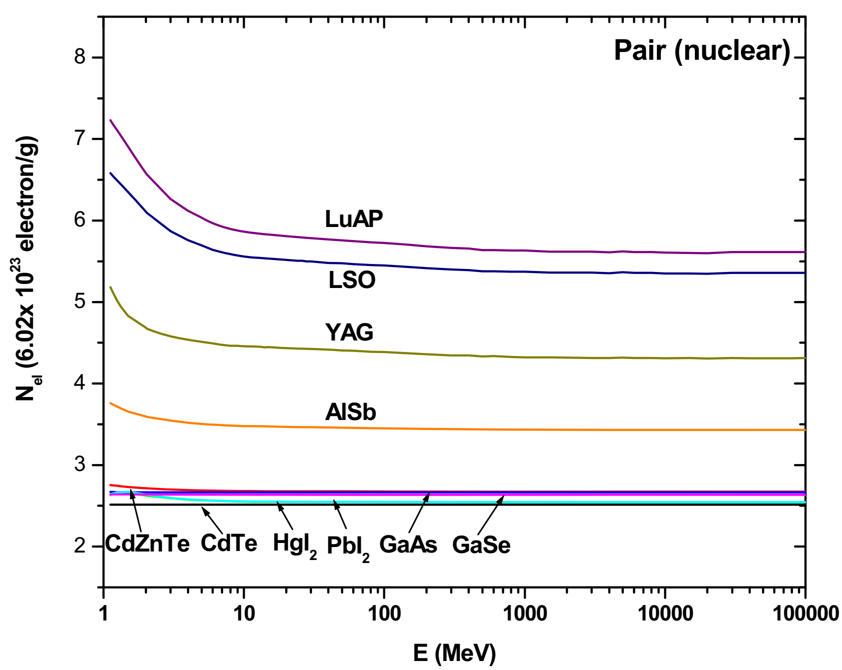

Fig. 12 Effective electron densities (nuclear pair) of semiconductor and scintillation detectors

detectors. The variation in Z_{eff} depends on the respective proportion of the atomic number of the elements in the detectors. The variation in N_{el} for Compton (coherent) scattering in Fig. 7 can be explained using the partial photon interaction process similar to the Fig. 6.

3.4 Coherent (Rayleigh) scattering

For the coherent scattering, the variations in Z_{eff} and N_{el} with photon energy are shown in Figs. 8 and 9, respectively. From Fig. 8, it is found that Z_{eff} is constant except for the

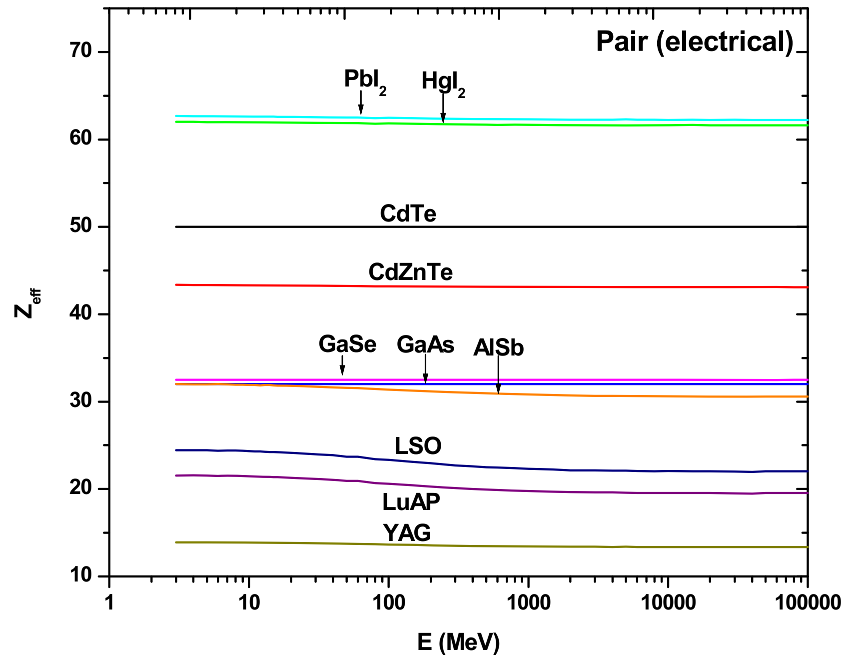

Fig. 13 Effective atomic numbers (electrical pair) of semiconductor and scintillation detectors

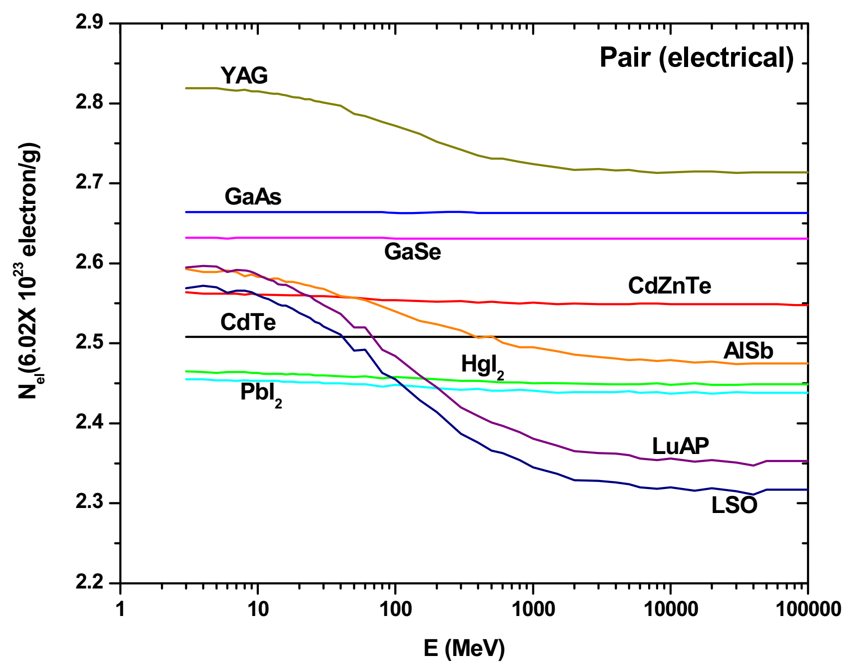

Fig. 14 Effective electron densities (electrical pair) of semiconductor and scintillation detectors

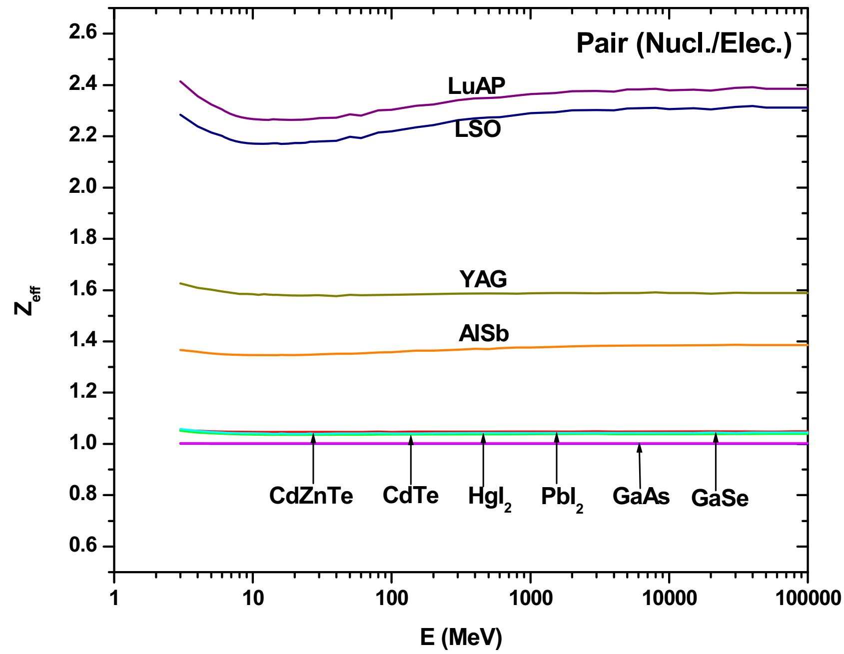

Fig. 15 Effective atomic numbers (nuclear/electrical) of semiconductor and scintillation detectors

Table 1 Comparison of effective atomic numbers by Direct-Z_{eff} and ZXCOM

Energy (MeV)	Methods	CdTe	CdZnTe	HgI2	GaAs	PbI_2	GaSe	AlSb	YAG	LSO	LuAP
10^{-2}	Direct-Z_{eff}	50.24	41.43	60.60	32.10	61.64	32.71	45.87	26.00	64.73	62.49
	ZXCOM	50.19	46.29	66.51	32.02	67.32	32.53	45.80	28.64	64.62	62.23
10^{-1}	Direct-Z_{eff}	50.22	47.80	68.87	32.07	70.44	32.67	48.06	25.19	65.55	63.95
	ZXCOM	50.25	47.91	63.92	32.01	64.71	32.58	47.44	21.95	62.67	60.56
10^{0}	Direct-Z_{eff}	50.02	43.62	63.40	32.00	64.33	32.50	32.77	14.04	27.27	23.98
	ZXCOM	50.36	48.77	71.92	32.12	73.76	32.79	49.61	34.99	68.37	67.54
10^{1}	Direct-Z_{eff}	50.05	44.58	63.60	32.02	64.48	32.54	38.09	16.79	38.26	33.92
	ZXCOM	50.41	49.04	73.59	32.13	75.57	32.82	49.81	35.34	68.95	68.29
10^{2}	Direct-Z_{eff}	50.07	45.13	63.98	32.03	64.92	32.56	41.79	20.45	49.07	44.63
	ZXCOM	50.50	49.44	75.72	32.15	77.80	32.87	50.09	36.03	69.59	69.15
10^{3}	Direct-Z_{eff}	50.07	45.15	63.94	32.03	64.92	32.56	41.96	20.64	49.52	45.11
	ZXCOM	50.50	49.44	75.72	32.15	77.80	32.87	50.09	36.03	69.59	69.15
10^{4}	Direct-Z_{eff}	50.07	45.14	63.96	32.03	64.89	32.56	41.92	20.63	49.45	45.03
	ZXCOM	50.50	49.44	75.72	32.15	77.80	32.87	50.09	36.03	69.59	69.15
10^{5}	Direct-Z_{eff}	50.07	45.14	63.93	32.03	64.91	32.56	41.93	20.62	49.45	45.04
	ZXCOM	50.66	49.90	77.52	32.18	79.61	32.95	50.32	36.58	70.14	69.86

detectors that increase in energy from 1 keV to 1 MeV. Beyond 1 MeV, Z_{eff} is independent of photon energy for all the detectors. The variation in N_{el} for Compton (coherent) scattering in Fig. 9 can be explained similarly to Fig. 8.

Figure 10 shows the variation in the coherent-to-incoherent scattering ratio (Coh./Incoh.) for the Z_{eff} of all the detectors and is constant for photon energies beyond 1 MeV.

3.5 Pair production (nuclear field)

For pair production in the nuclear field, the variations in Z_{eff} and N_{el} with photon energy are shown in Figs. 11 and 12, respectively. From Fig. 11, it is found that Z_{eff} slightly decreases (for few detectors) with an increase in photon energy ranging from 1 to 20 MeV, and then, it is almost independent of photon energy for all other detectors. The variation in N_{el} for pair production (nuclear) in Fig. 12 can be explained similarly to Fig. 11.

3.6 Pair production (electric field)

For the pair production in the electric field, the variations in Z_{eff} and N_{el} with photon energy are shown in Figs. 13 and 14, respectively. From Fig. 13, it is found that Z_{eff} is independent of photon energy, except for the YAG, AlSb, LSO and LuAP detectors. Also, Z_{eff} for the YAG, AlSb, LSO, and LuAP detectors becomes independent of photon energy beyond 1000 MeV. The highest-Z containing detector (PbI_2) is found to have the highest Z_{eff}. The variation in N_{el} for pair production (electric) in Fig. 14 can be explained similarly to Fig. 13.

In Fig. 15, the ratio of effective atomic numbers for pair production for nuclear to electric is shown and found to be independent from energy, except for LuAP and LSO.

3.7 Comparison with ZXCOM

The effective atomic numbers calculated using Eq. (4) were compared with ZXCOM software [29]. In the ZXCOM process, the effective atomic number is characterized using Rayleigh and Compton scattering. İçelli [30] showed the theoretical and computational approach for obtaining data from the R/C ratio (R). Details of the ZXCOM method and theoretical approach for calculation are reported in the literature [29, 30]. The effective atomic numbers using both methods are given in Table 1. From Table 1, it is found that effective atomic numbers calculated using direct-Z_{eff} and ZXCOM are comparable with each other, with an exception of a few energies.

4 Conclusion

In the present investigation, we have calculated mass attenuation coefficients, effective atomic numbers, and effective electron densities for semiconductor and scintillation detectors. The investigation is summarized below:

- Effective atomic numbers for semiconductor and scintillation detectors are found to be constant in the pair production region (E > 100 MeV).
- Effective atomic numbers calculated using the direct-Z_{eff} and ZXCOM programs are found to be comparable.
- Efficiencies of semiconductor and scintillation detectors are presented in terms of effective atomic numbers.

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