Electron, Proton, and Alpha Stopping Powers of Polyvinyl toluene (PVT) Scintillator Crystal

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Abstract
The stopping powers of electrons, protons, and alpha particles incident with different energies on polyvinyl toluene (PVT), which used as a crystal in scintillator detectors, have been calculated using the codes of National Institute of Standards and Technology (NIST). For electrons, the collision and radiative stopping powers were calculated and for protons and alpha particles, the electronic and nuclear stopping powers were investigated. The behaviors of the calculated stopping power have been studied and explained. The obtained results strongly suggest that if one used PVT as a detector crystal, they must be shielded against tested particles.

Keywords: Stopping Power; PVT; Scintillator Crystal; Electron; Proton; Alpha

1. Introduction
One of the available and effective methods of radiation detection is the process of measuring and detecting radiation using scintillator detectors, and it's used in the spectroscopy for a wide spectrum of radiation types [1]. Scintillator detectors are materials that release a flash when the radiation falls on it. By measuring the intensity and amount of this scintillating light, one can know the intensity and energy of radiation, and therefore, there are several specifications that must be provided in these materials in order to achieve the purpose intended to be used, which is their ability to convert the radiation energy to the light can be detected with high efficiency. This ability must be linearly proportional to the radiation energy. The medium must also be able to transmit this flash within a measurable wavelength with the necessity that the time between radiation absorption and scintillating light be as low as possible in addition to the quality of the optical material and that it be reflection coefficient, as in glass [2].
There are several types of scintillator materials, including organic scintillating materials and inorganic scintillating materials. The working way of the first type is that when these materials are exposed to radiation, they absorb the radiation energy, and which leads to the irritation of the electrons in the ground's state $S_0$ leading to raising them to the individual higher excitement states. These substances and an internal transmission of these electrons occur to return to the $S_{10}$ state that is allowed to return from it. In this case, a photon is emitting in the form of a flash that can be measured [3]. Among the types of these organic scintillator materials are Anthracene and Polyvinyltoluene (PVT) [4], which are pure organic compounds and are usually crystalline or in the form of a solution when dissolved with the addition of some substances that cause shafted in the wavelength of the scintillating light. This type of detectors is used to detect radioactivity when it can be dissolved in the solution. In this case, the detection efficiency is 100%, as well as plastic scintillating materials such as PVT, which are characterized by their ability to form in several different shapes and sizes.

On the other hand, the stopping power is an important parameter and must be known when making a detector of any substance, especially scintillator materials [4]. This is due to the fact that if a scintillator detector made from an organic material is used to measure gamma rays, for example (which is impossible to emit on its own, and is always emitted after the parent nucleus emits a beta or alpha particle, especially in nuclei of natural origin), it is possible that some flashes may be recorded of the interaction of particles associated with gamma rays such as beta and alpha with gamma flashes. In addition to this, these beta and alpha particles can cause significant effects in the scintillator detector by irradiating it, leading to a decrease in the efficiency of its detection ability [5].

However, in this paper, the stopping power of electrons, protons, and alpha particles in PVT material that used in organic scintillator detectors have been measured using the codes established by "National Institute of Standards and Technology (NIST)" [6].

2. PVT (Polyvinyl toluene)

PVT composed from a linear alkyl-benzenes that have formula $[\text{CH}_2\text{CH}(\text{C}_6\text{H}_4\text{CH}_3)]_n$. PVT is industrial polymer and commercially mixed with methyl styrene isomers [7]. The chemical formula is shown in figure (1), and its properties are listed in table (1) [8].

![Figure (1); the chimachal fomula of PVT [7]](image-url)
Table (1); the properties of PVT polymer [8]. These properties data are given in their standard state (at 25 °C, 100 kPa).

| Property                    | Value                   |
|-----------------------------|-------------------------|
| Chemical formula            | C₉H₁₀                   |
| Density (g/cm³)             | 1.032                   |
| Mean Excitation Energy      | 64.70 eV                |
| Molar mass                  | 118.179 g.mol⁻¹         |
| Appearance                  | colorless liquid        |
| Boiling point               | 170–175 °C              |

| COMPOSITION                  | Fraction by weight |
|------------------------------|--------------------|
| Atomic number 1              | 0.085              |
| Atomic number 6              | 0.915              |

3. The Stopping Power

The electronic stopping power can be defined as the process of losing energy to the particles and ions charged during the path unit and that the process of calculating it relied on the basic factors of the incident particle and the target material through speed, charge and mass in relation to the incident particle as well as on the characteristic of that target (i.e. the target material) so therefore, the process differs energy loss through the nature and type of incident particle. Whereas, the nuclear stopping power can be defined as the average rate of energy loss per unit path length due to the transfer of energy to recoiling atoms in elastic collisions, which is contribute in the total stopping power for heavy charged particles only.

By using the first Born approximation, Bethe (in 1930) depends on quantum mechanics approach [9] to calculate the electronic stopping power (the electronic energy loss). However, the cross section of stooping in c.g.s. units, is given by [10]:

\[ S_e = \frac{4\pi Z_1^2 e^4}{m v^2} Z_2 \ln \left( \frac{2 m v^2}{I} \right) \]  

where \( v \) is the projectile’s speed, \( Z_1 e \) is the nuclear charge of the projectile, \( Z_2 e \) is the nuclear charge of the target, \( m \) and \( e \) are mass and charge of the electron, and \( I \) is the mean excitation energy of the target.

By adopting the relativistic effects, equation (1) becomes:

\[ S_e = \frac{4\pi Z_1^2 e^4}{m v^2} Z_2 \left[ \ln \left( \frac{2 m v^2}{I} \right) - \ln(1 - \beta) - \beta^2 \right] \]  

\[ \beta = \frac{v}{c} \]  

where \( c \) is the speed of light.

The linear electronic stopping power is related to the electronic stopping cross section as follows;

\[ S_{lin} = -\frac{dE}{dx} = n S_e \]  

where \( n \) is the no. of target atoms. The mass stopping power can be given by;

\[ S_{lin}/\rho = \frac{4\pi Z_1^2 m c^2}{\beta^2} \frac{1}{u} \frac{Z_2}{A_2} Z_1^2 \left[ \ln \left( \frac{2 m v^2}{I} \right) - \ln(1 - \beta) - \beta^2 \right] \]
\( S_{\text{in/r}} = (0.307075 \, MeV \, cm^2/g) \frac{Z_2}{A_2} Z_1^2 \left[ \ln \left( \frac{2m\nu^2}{I} \right) - \ln(1 - \beta) - \beta^2 \right] \ldots (6) \)

where \( r_e^2 = \frac{e^2}{mc^2} \) is the classical electron radius, \( u \) is the atomic mass unit, \( A_2 \) is the relative isotopic mass of the target atom, and standard values of the various atomic constants have been used.

In addition, the nuclear stopping power is contribute to total stopping power in the low energy incident heavy particles. When the projectile energy becomes high, nuclear stopping is not important, and can be neglected in the calculations. For practical calculations, nuclear stopping is given by [11]

\[ S_n(E) = \frac{8.4621 \times 10^{-15} Z_1 Z_2 M_1 S_n(\varepsilon)}{(M_1 + M_2)(Z_1^{0.23} + Z_2^{0.23})} \, eV/atom/cm^2 \ldots (7) \]

where \( \varepsilon \) is the reduced energy and calculated from

\[ \varepsilon = \frac{32.53 M_1 E}{Z_1 Z_2 (M_1 + M_2)(Z_1^{0.23} + Z_2^{0.23})} \ldots (8) \]

where \( E \) is the energy in keV, and \( M_1, M_2 \) are the masses of projectile and target atom, respectively. The reduced nuclear stopping is then given by

\[ S_n(\varepsilon) = \ln \left( 1 + 1.1383 \varepsilon \right) \frac{2 \left[ \varepsilon + 0.01321 \varepsilon^{0.21226} + 0.19593 \varepsilon^{0.5} \right]}{2[\varepsilon + 0.01321 \varepsilon^{0.21226} + 0.19593 \varepsilon^{0.5}]} \quad \text{For} \quad \varepsilon \leq 30 \ldots (9) \]

\[ S_n(\varepsilon) = \frac{\ln(\varepsilon)}{2 \varepsilon} \ldots (10) \]

Finally, there are some terms used in the stopping power [12], which are 1- Collision stopping power: "average rate of energy loss per unit path length, due to Coulomb collisions that result in the ionization and excitation of atoms. For heavy charged particles, the collision stopping power is often called electronic stopping power". 2- Radiative stopping power: "average rate of energy loss per unit path length due to collisions with atoms and atomic electrons in which bremsstrahlung quanta are emitted", which needed only for electrons. 3- Nuclear stopping power: "average rate of energy loss per unit path length due to the transfer of energy to recoiling atoms in elastic collisions", which is important only for heavy charged particles. 4- The total stopping power: for electrons, "the sum of the collision and radiative stopping powers"; for protons and helium ions, "the sum of collision and nuclear stopping powers".

4. Results and Discussions

In this paper, the stopping power of incident electrons (for both collisional and radiative), protons and alpha particles (also for both presses; electronic and nuclear) incident on PVT martial (that used as a crystal in the scintillator detector) have been calculated using codes of NIST that depends on the equations illustrated in the previous section. The overall calculated results of the stopping power of electrons incident on PVT have been showed in figure (2). In this figure, the collision stopping power is predominant approximately up to 10 MeV and the large contribution of
radiative stopping power is begin after (around) 100 MeV. In general, the total stopping power decreases with incident electron energy up to 1 MeV and after 10 MeV became slowly increasing. Also, there are a saturation region between 50 keV and 10 MeV, and this energy window is very important in the manufacturing of scintillator detectors based on PVT material.

In figures (3 and 4), that represented the overall calculated results of the incident proton and alpha particles on PVT respectively, the behaviors are same regardless of the values of stopping powers. These behaviors of the proton and alpha particles prompt us to conclude that in the case of making a scintillator detector dependent on PVT crystal, it must be shielded against these particles because as we know this detector is used to detect gamma rays only.

Finally, as its expected, the values of the stopping power are higher for alpha particles and the lower values is for electrons.

![Figure (2); The collision, radiative, and total stopping powers of electrons incident on PVT as a function of energy](image-url)
Figure (3): The electronic, nuclear, and total stopping powers of electrons incident on PVT as a function of energy

Figure (4): as figure (3) but for alpha particles
5. Conclusions

From the results of this paper, and if we want to use PVT as a crystal in gamma radiation scintillator detector, one can conclude that for all investigated particles (electron, beta, and alpha) the manufacturer must be used shield against these particles. Furthermore, the electrons total stopping power of PVT decreases with respect to incident energy, then saturated for the range 50 keV to 10 MeV and after that increasing. But for proton and alpha particles, it decreases till to specific energy and then increasing.

6. References

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