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Experimental Study to Determine the Backscattering, Asymmetry, and Tailing Factors for Some Elements in the Atomic Number Range of 4≤Z≤48 at 59.54 keV Using the Gamma Backscattering Method

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Abstract: This experimental study has been carried out by using gamma backscattering method which is a non-destructive method. Some elements which are in the atomic number range of 4≤Z≤48 have been used as backscatterer samples to investigate the variation of backscattering factor, asymmetry factor, and tailing factor with atomic number. These samples were irradiated by γ-rays of 59.54 keV energy emitted from a 10 μCi ^{241}Am point radioactive source. To count the backscattered photons from samples, a high purity germanium detector (HPGe) with a resolution of 182 eV at 5.9 keV and active area of 200 mm^2 was used. It was concluded that the coherent to backscattering ratio, asymmetry factor, and tailing factor increased with increasing atomic number, but the count rate and backscattering factor decreased.

Gama Geri Saçılma Yöntemini Kullanarak 59.54 keV'de 4≤Z≤48 Atom Numarası Aralığındaki Bazı Elementler İçin Geri Saçılma, Asimetri ve Kuyruklanma Faktörlerini Belirlemeye Yönelik Deneysel Çalışma

Anahtar Kelimeler
Geri saçılma,
Geri saçılma faktörü,
Asimetri faktörü,
Kuyruklanma faktörü,
HPGe dedektör

Öz: Bu deneysel çalışma, tahribatsız bir yöntem olan gama geri saçılma yöntemi kullanılarak gerçekleştirilmiştir. Geri saçılma faktörü, asimetri faktörü ve kuyruklanma faktörünün atom numarasına göre değişimini araştırmak için, geri saçıcı numuneler olarak 4≤Z≤48 atom numarası aralığındaki bazı elementler kullanılmıştır. Bu numuneler, 10 μCi ^{241}Am radyoaktif nokta kaynaktan yayılan 59.54 keV enerjili γ-ışınları ile ışınlanmıştır. Numunelerden geri saçılan fotonları saymak için, 5.9 keV'de 182 eV çözünürlüğe ve 200 mm^2 aktif alana sahip yüksek saflıkta germanyum dedektörü (HPGe) kullanıldı. Koherent/geri saçılma oranı, asimetri faktörü ve kuyruklama faktörünün artan atom numarası ile arttığı, ancak sayma hızı ve geri saçılma faktörünün azaldığı sonucuna varıldı.

1. INTRODUCTION

Backscattering (i.e., backscatter) is defined as the reflection of radiation or particles back to the direction from which they came. Backscattering has many important application areas as astronomy, radar systems (especially weather radar), radiation dosimetry, fiber optics, photography, X-ray imaging, neutron or X-ray spectroscopy, and medical ultrasonography. The gamma backscattering method is a non-destructive method. This method can be used to determine physical parameters as thickness (or saturation thickness), density, and shape of backscattering samples (or materials). When the material used as target are irradiated by gamma photons, the gamma photons are backscattered from the interior of the target and then these gamma photons backscattered backwards are detected using a detector in this method.

There are many studies with regard gamma backscattering in the literature. Because the backscattering method is very useful, it is used to determine parameters such as effective atomic number, saturation thickness, and albedo factor for a material. Udagani [1] studied experimentally gamma backscattering and saturation thickness for granite and glass using ^{137}Cs radioactive source and NaI(Tl) detector at 180° scattering angle. Then, Udagani [2] investigated gamma ray backscattering for water, kerosene, petrol, and admixture of kerosene and petrol.

He concluded that the gamma backscattering technique is very useful and sensitive analytical technique for performing quantitative analysis of samples. Almayahi [3] measured the backscattering factor of gamma rays for pure concretes of different thicknesses using gamma energies in range of 0.088 MeV to 1.253 MeV and a NaI(Tl) scintillation detector. He concluded that the backscattering factor increased with increasing target thickness and gamma photon energy. However, he observed that the backscattering factor remains constant at a certain thickness value called the saturation thickness. Singh et al. [4] measured effective atomic number of composite materials at 662 keV using gamma backscattering technique. They investigated the effect of target thickness on intensity distribution of gamma photons. These gamma photons are multiply backscattered from targets. They found that intensity of multiply backscattering increased with increasing target thickness and finally saturated. Also, Singh et al. [5] determined the effective atomic number of biomedical samples the same technique. Kiran et al. [6] carried out an experimental study to determine effective atomic number of composite materials by Compton scattering. Then, Kiran et al. [7] calculated the effective atomic number of some construction materials for gamma photons scattered in backward direction of 90° to incident photon and detected the backscattered gamma photons by a NaI(Tl) detector. Uzunoğlu et al. [8] investigated experimentally the multiple scattered fraction as a function of target thickness for HgO and PbO at a scattering angle of 168°, and incident gamma photon energy of 59.54 keV. Backscattered photons were collected using a HPGe semiconductor detector in their study. Ravindraswami et al. [9] studied experimentally selected polymers by multiple scattering of gamma rays of 662 keV energy and detected the backscattered photons by a NaI(Tl) detector. In their study, the detector was placed at an angle of 90° to the incident gamma photons. They compared their experimental results with the results obtained from Monte Carlo N-particle simulation code. Sharma et al. [10] investigated effective atomic numbers for binary alloys as PbSn, PbZn and ZnSn at 662 keV using gamma backscattering technique. They compared their experimental results with the theoretical ones which were obtained from WinXCom, and observed that there is a good agreement between theoretical and experimental results. Wirawan et al. [11] performed simulations using Monte Carlo GEANT4 toolkit for analyzing the gamma backscattering of different flaw types and their orientations. Sabharwal et al. [12] measured albedo factors for targets of different atomic numbers and various target thicknesses using backscattered gamma photons of 279, 320, 511 and 662 keV. They detected the backscattered gamma photons by an NaI(Tl) scintillation detector and found that the energy albedos decreased with the increase in the atomic number of the target and incident gamma photon energy. Naji et al. [13] examined the effect of backscattering gamma radiation on X-ray image contrast. Qutub MAZ. [14] investigated the photon backscattering for various stainless-steel thicknesses. He carried out this work using the FLUKA code for Monte Carlo simulations in the 0.25- 20 MeV energy range.

Özdemir et al. [15] determined asymmetry factor and energy shifts of the K_β and K_α peaks for the transition metals by using a Si(Li) detector at temperatures between 40 and 400 °C. Gotmar et al. [16] explored the peak tailing in linear chromatography. They mentioned that peak tealing reduces often considerably the resolution between analytes and causes band interference. In addition, they presented that it prevents an accurate interpretation of UV spectra. Also, peak tealing reduces the accuracy of quantitative results. Therefore, the tailing (or fronting) of the peak has an undesirable effect, which is a problem in XRF peak analysis as well as in chromatography. Wahab et al. [17] carried out detection and quantitation of fronting, tailing. In addition, they investigated the effects of tailing and fronting on asymmetry measurements.

Parameters such as peak height, area, and resolution are very important for peak shape analysis. Gaussian function is used to assess problems in a peak such as tailing (or fronting), shouldering, or siplitting. The Gaussian function, which is widely used, enables qualitative and quantitative assessment of individual contributions to the overall peak distortion. But this situation is rarely noticed and it is never quantified. Therefore, the signal to noise ratio should be determined for XRF analysis and this ratio should be high.

In this experimental study, peak asymmetry has been used as a way to quantify the contributions of fronting and tailing to non-Gaussian peaks with gamma backscattering method. The variation of count rate, backscattering factor, coherent to backscattering ratio, asymmetry factor (A_s) and tailing factor (*TF*) with atomic number were investigated using backscattered peaks of some elements which are in $4 \leq Z \leq 48$ atomic number range.

2. MATERIAL AND METHODS

2.1. Experimental Setup and Acquisition System

In this work, some elements which are in the atomic number range of $4 \leq Z \leq 48$ were used as samples for gamma backscattering method. These elements in the form of foil were Be, Cu, Nb and Cd. The masses of these samples were 0.47877, 0.16778, 0.27006 and 0.57235, respectively. These samples were irradiated with gamma rays of 59.54 keV energy emitted from ^{241}Am point radioactive source which has an activity of 10 µCi. High-Purity Germanium (HPGe) detector, which has a DSG planar high purity germanium crystal with an active diameter of 16 mm, was used to detect gamma photons backscattered. In addition, this detector has an active area of 200 mm^2, sensitive depth (i.e., active thickness) of 10 mm, Be window thickness of 0.12 mm, distance from window (i.e., distance between Ge crystal and Be window) of 5 mm, and a resolution of 182 eV at 5.9 keV. A bias voltage of -1500 V was applied to the detector.

The time used as the data acquisition time was 18000 s for each measurement. The channel was set to 4096 for the multichannel analyzer. To ensure optimum detector performance specified by the manufacturers, the time constant of the amplifier was set to 6 µs. MAESTRO, which is a computer program, was used to govern and control the operating parameters of the system. The Origin 7.5 software program was used to analyze the pulse height spectra acquired with and without the backscattered target.

The experimental setup of the present measurements for backscattering method is shown in Figure1. According to Figure 1, the distance between the point radioactive source and the HPGe detector is 1.9 cm. Also, the distance between the point radioactive source and sample is 1 mm. The centers of the HPGe detector, radioactive point source, and target are on the same axis. The backscattering angle was 180°. HPGe detectors should always be kept at low temperatures such as liquid nitrogen temperature, which is -196°C. For this, detector crystal is placed in a dewar containing liquid nitrogen.

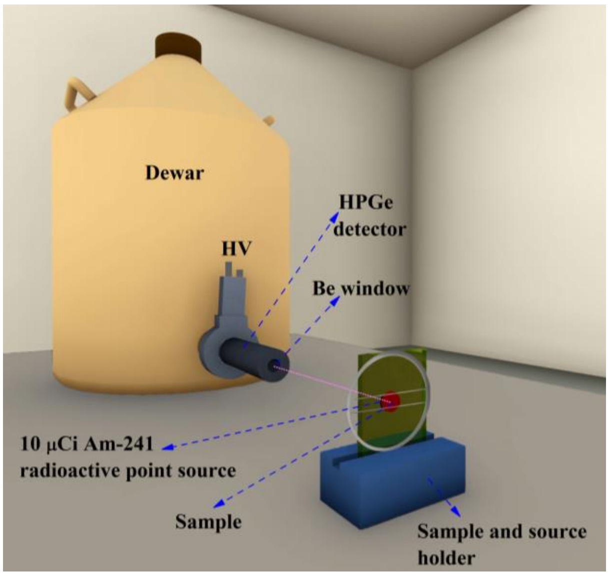

Figure 1. Experimental setup of the present measurements for backscattering method

2.2. Calculation Method of Backscattering, Asymmetry and Tailing Factors

The gamma backscattering method, which is dependent on the sample property, is based on the Compton scattering effect. Compton scattering is the scattering of a high-energy photon from an electron, which is generally considered to be at rest and free, or from a bound electron whose binding energy is small compared to the energy of the incident photon. Compton scattering is dominant for light (or low atomic number) elements. The backscattered gamma rays are those scattered through a large angle (> 120°) by the shielding or target. Compton scattering energy (or backscattering energy) varies with angle. When angle approaches 180°, the maximum energy to sample is transferred. In this study, the backscattering angle is 180° as seen from Figure 1. The energy dependence of backscattered gamma photons as a function of angle is given by the following formula:

$$E_s = \frac{E_i}{[1 + (E_i/m_0c^2)(1 - cos\,\theta)]} \tag{1}$$

where E_i, E_s, m_0, c and θ are the energy of incident photon, the energy of scattered (or backscattered) photon, the rest mass of the electron, the speed of light, and the scattering (or backscattering) angle, respectively. In this equation, m_0c^2 is the rest mass energy of an electron and its value is 511 keV.

The backscattering factor depends on some variables. These are thickness of the backing material, kinetic energy of particle, and atomic number of the backing material. To understand the effect of backscattering, a source backscattering factor (F_b) must be calculated [3, 18]. It can be defined by the following equation:

$$F_b = \frac{N_b}{N_i} \times 100\% \tag{2}$$

where N_b and N_i are number of photons counted with source backing, and number of photons counted without source backing, respectively.

An ideal peak has a sharp symmetrical shape on a flat baseline such as a Gaussian peak. However, a peak can deviate from this ideal form for different reasons. These are that the peak can be asymmetrical, flatten and broader, or the baseline can rise.

Asymmetry factor (A_s) describes how symmetrical a peak is, as the name indicates. In addition, it also indicates whether a peak has either fronting or tailing. Namely, the asymmetry factor is a way of measuring peak tailing (or fronting). It is related to the distances from the center of the peak to either side of the peak (i.e, right or left of peak). Asymmetry factor is calculated by the following equation [17]: 14

$$A_s = (bc/ca)_{10\%} \tag{3}$$

where bc is the distance from the centre line of the peak, which is a perpendicular line drawn from maximum point of the peak, to the left back slope of the peak measured at 10% of peak height. Also, ca is the distance from the centre line of the peak to the right front slope of peak measured at 10% of peak height. All A_s measurements were made for 10% of the maximum peak height. The value of A_s is equal to 1 for exactly symmetrical peaks. If the value of A_s is less than 1, fronting is observed at the peak. On the contrary, if A_s is greater than 1, tailing is observed at the peak.

Peak fronting occurs when the first half is broader than the second half, and the second half is narrower in an asymmetric peak. The inverse of peak fronting is called as peak tailing. Such a peak is asymmetrical and also second half is broader than the front half of peak. Peak tailing is calculated by the following equation [17]:

$$TF = (ab/2ac)_{5\%} \tag{4}$$

where ab is defined as the distance from the right front slope of the peak to the left back slope. Also, ac is the distance from the centre line of the peak to the right front slope. All TF measurements were made for 5% of the maximum peak height.

3. RESULTS AND DISCUSSION

For this study, the experimental measurements were performed by using gamma backscattering method at scattering angle of 180° as seen from Figure1. Be, Cu, Nb, and Cd which are in the atomic number range of $4 \leq Z \leq 48$ and in the form of foil were used as samples. These samples were irradiated by γ-rays of 59.54 keV energy emitted from ^{241}Am point radioactive source, which has an activity of 10 μCi. Gamma photons backscattered from these samples were counted using an HPGe detector. Then, the spectra were obtained for with and without backscattering (or backscatterer) sample. The typical backscattering spectra obtained with and without a Be sample were shown in Figure 2. The value of energy for backscattered peak was calculated by using Equation 1. For this study, the energy of the backscattered peak was defined as 48.287 keV.

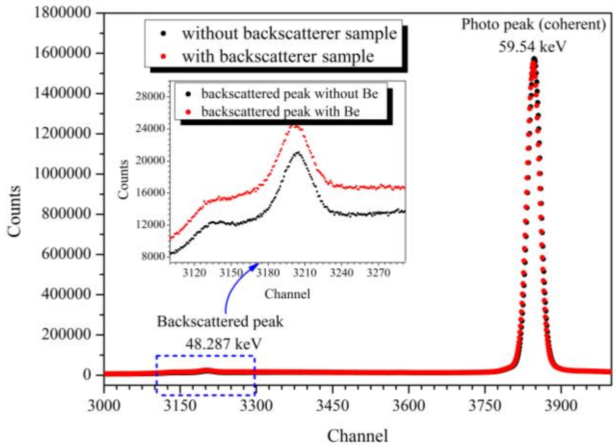

Figure 2. Typical backscattering spectra obtained with and without a Be sample

To define the peak area under the backscattering peak, 'substract baseline' mode was first used in the peak analyzer of Origin 7.5 program. The baseline subtraction is used to estimate and eliminate background noise. Signals with intensity lower than a threshold value are considered to be noise. So, these undesirable background signals must be removed of peak or spectrum. Because of the shifts away from a Gaussian peak (that is, because it is a peak that cannot be fitted to the gaussian function), it is necessary to select the correct peak regions. Region of interest (ROI) was defined between the start and stop channels of peak to determine the net peak areas under these backscattering peaks [1]. Then, the area under the backscatter peak was calculated by summing the counts corresponding to each channel in this region. For this total area of peak in the ROI region, the counts were integrated by Origin 7.5 program. The representation for ROI analysis under the backscattering peak on a typical spectrum obtained from Be was shown in Figure 3.

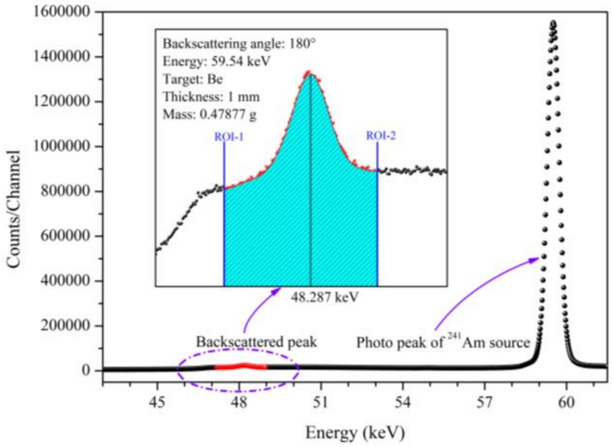

Figure 3. Representation for ROI analysis under the backscattering peak on a typical spectrum obtained from Be

As seen from Figure 3, ROI-1 is the start point and ROI-2 is the stop point of the ROI region of the backscattering peak. The values of counts under ROI, count rate, backscattering factor (F_b) (which is calculated using Equation 2), and coherent to backscattering intensity ratio (Coherent/BS) were given in Table 1. Also, the variations of these parameters dealing with backscattering with various atomic numbers were shown in Figure 4.

When the Table 1 and Figure 4 are examined, it is seen that the counts under ROI, the count rate, and backscattering factor decrease with increasing atomic number, but the coherent to backscattering intensity ratio increases. The experimentally measured values of these parameters were fitted to the second-degree polynomial curves. The fit functions and the correlation coefficients obtained for these fit functions are also given in Figure 4. It is seen that these correlation coefficients are quite high from Figure 4.

Table 1. The values of measured parameters dealing with backscattering for various atomic number

Elements	Z	Counts Under ROI	Count Rate	F_b	Coherent/BS
Be	4	285531	15.863	1.092	170.709
Cu	29	269578	14.977	1.031	180.352
Nb	41	257113	14.284	0.984	188.297
Cd	48	234241	13.013	0.911	203.211

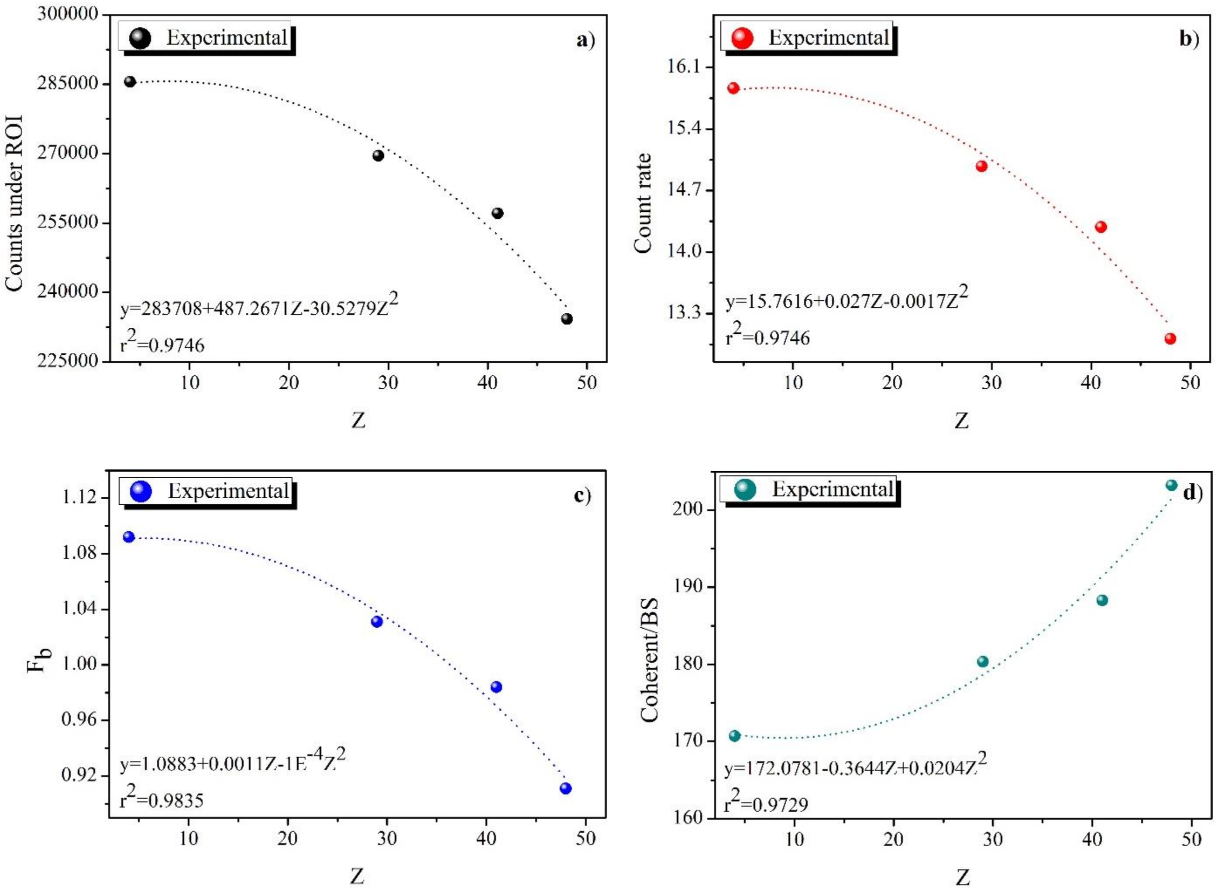

Figure 4. Variation of a) counts under ROI, b) count rate, c) backscattering factor (F_b), and d) coherent to backscattering (Coherent/BS) intensity ratio as a function of atomic number (Z)

As a result of the interaction of high-energy rays with target, either complete absorption or scattering occurs for each interaction. When electromagnetic radiation is sent on any material, photons can interact with bonded atomic electrons, free electrons, the nucleus or the Coulomb field of electrons, nucleons or the whole nucleus, or they can pass without any interaction. Interactions with energies up to 10 MeV often result in any of the events such as photoelectricity, Compton or pair production [19]. However, cross sections can be used to determine what kind of the interactions occur when a photon of 59.54 keV energy interacts with the material. For this study, the coherent, incoherent (Compton or backscattering), photoelectric cross sections for 59.54 keV energy, and their contributions to total photon interaction (%) were calculated using WinXCOM program. Then, these results were given in Table 2. According to Table 2, there is a relationship such as Compton>coherent>photoelectric between scattering and photoelectric effects of the elements with low atomic number. Conversely, it is obvious that there is a relationship such as photoelectric>coherent>Compton for elements with large atomic numbers.

Table 2. The cross sections obtained for 59.54 keV energy using WinXCOM program and their contributions to total photon interaction (%)

	Cross Sections (cm^2g^{-1})			The contributions to total photon interaction (%)		
Z	Coherent	Incoherent	Photoelectric	Coherent	Incoherent	Photoelectric
4	0.005	0.143	0.001	3.339	95.948	0.713
29	0.109	0.131	1.385	6.727	8.081	85.193
41	0.184	0.122	3.812	4.468	2.955	92.576
48	0.229	0.115	5.759	3.757	1.887	94.357

When photons are sent onto the target, these photons not only lose energy as they pass through the target, but also scatter at very small angles along their path. Single scattering occurs if there is only one scattering in a target, and multiple scattering can occur if there are more than once scatterings in a target. Photons scattered from a target that undergo re-scattering from neighboring atoms in target cause to multiple scattering [8]. The parameters such as photon energy, scattering angles, source and detector collimation, sample thickness, and density must be taken into account for the experimental determination of multiple scattering. In Compton scattering or backscattering, the incoming photon undergoes to multiple scattering in the sample before it leaves the sample. The multiple scatterings of photons occur as a hump on the left slope of the

Compton (or backscattering) peak. This hump is shown in Figure 5 for Be. Because the hump is on the left slope of the peak, peak fronting occurs, not tailing. The peaks, which has a such hump, are not perfect like the Gaussian peak, so they are not symmetrical. It is known that tailing or fronting is most clearly seen close to the baseline. A representation for measurement of peak tailing factor and asymmetry factor is given in Figure 5.

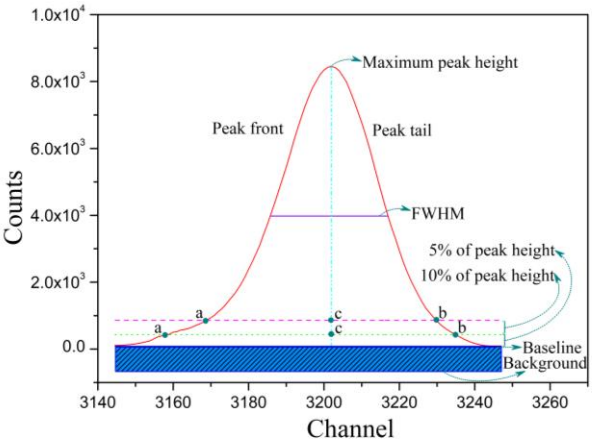

Figure 5. Representation and measurement of peak tailing factor and asymmetry factor

Asymmetry factors were calculated using Equation 3 at 10% of peak height. Also, tailing factors were calculated using Equation 4 at 5% of peak height. The channel to which the maximum peak height corresponds, asymmetry factor and tailing factor are given in Table 3. In addition, the number of channels to the left and right of backscattering peak is defined as A and B, respectively. The values of A and B are also given in Table 3 for both asymmetry factor and tailing factor. Thus, the amount of tailing at the backscattering peak was determined for various atomic numbers. When the Table 3 is examined, it can be concluded that A is bigger than B and there is a tailing on the left slope of backscattering peak. That is, there is peak fronting for a backscattering peak, which in this case TF is lower than 1. Also, it was found that the values of asymmetry factor and tailing factor approach 1 with increasing atomic number. Because, as the asymmetry factor is closer to 1, as the symmetry of backscattering peak is greater.

Table 3. The channel numbers of backscattering peak maximum for elements of various atomic numbers, the values of their asymmetry factors (A_s) and tailing factors (TF)

Z	Channel Peak Max.	A_s	A	B	TF	A	B
4	3201	0.763	38	29	0.924	46	39
29	3198	0.875	32	28	0.944	45	40
41	3195	0.897	29	26	0.950	40	36
48	3194	0.926	27	25	0.953	32	29

4. CONCLUSION

The experiments were carried out using gamma backscattering method in this study. The variation of count rate, backscattering factor, coherent to backscattering ratio, asymmetry factor (A_s) and tailing factor (TF) with atomic number were investigated for some elements which are in 4≤Z≤48 atomic number range. It is concluded that the count rate, and backscattering factor decrease with increasing atomic number, but the coherent to backscattering intensity ratio increases. Then, the variation of the interaction cross sections (the coherent, incoherent (Compton or backscattering), photoelectric) with atomic number and their contributions to total photon interaction (%) were defined for 59.54 keV energy using WinXCOM. Finally, how the asymmetry factor and peak tailing change with atomic number was investigated for asymmetric backscattering peaks. It was seen that the photoelectric absorption increases as the atomic number increases, the multiple scattering will decrease and therefore the peak tailing will also decrease. So, the contributions of multiple scattering on backscattering peak were quantified. Because the backscattering method is nondestructive method, it can be used for qualitative and quantitative analysis of compounds, alloys, and composite materials.

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