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# Alpha-Particle Spectroscopy and Ranges in Air

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**Abstract:** ***The present study investigated energies of alpha-particles emitted by the triple-alpha sources ($^{239}$Pu, $^{241}$Am and $^{244}$Cm) in a vacuum and measure the alpha particle properties at different pressures. The absolute activities for the radioisotopes in the triple alpha source ($^{239}$Pu, $^{241}$Am and $^{244}$Cm) were found to be 678·25±26·0$s^{-1}$,631·97±25·1$s^{-1}$ and 146·08±12·1$s^{-1}$ respectively with ranges experimentally found to be 4·29±2·1cm, 4·90±2·2cm and 5·33±2·3cm respectively in air at STP. These values compare very well with known values in air at STP. Increases in energy peak when Poison error is assumed (FWHM increases) leads to increase in air pressure; a condition of energy straggling in the broadening of the peaks was also observed.***

**Keywords:** Air, Alpha particle, Energy peaks, Poison error, Radioisotope, Spectroscopy, Triple-alpha

## 1. Introduction

Alpha-particle spectrometry gives information on the energy of radiation, unlike Geiger-Muller tubes which determine only the count rate. Alpha emitters are used in smoke alarms in the form of $^{241}$Am, which ionises air in order to create an electrical current, which is interrupted in the presence of smoke. Other uses include $^{226}$Ra, used in breast cancer treatment, and $^{210}$Po which is used in industry to reduce static charge [1]. Since alpha particles emitted have a characteristic energy depending on the nucleus which is emitted, and the daughter product, it is possible to identify the origin of the primary radiation [2]. Recently, the field of alpha spectroscopy has gained recognition in nuclear measurement as well as the quantification and identification of alpha emitting radionuclides plays a major role in radiation protection. As the focus in the nuclear industry continues to shift to waste management, site decommissioning and decontamination, the usefulness of alpha particle spectroscopy will continue to grow [3].

Since the mid-1960's great advances with semiconductor detectors have been made. These are now routinely used for alpha spectrometry and they can also be employed for detection and spectrometry of fission fragments, internal conversion electrons, and even x-rays and gamma rays. The average energy required to produce an ion-pair in typical semiconductor materials (e.g. silicon or germanium) is an order of magnitude smaller than in gases which leads to extremely good energy resolution. Also these solid materials have a much higher density than gas-filled detectors which results in compact devices with high intrinsic detection efficiency and fast response [4]. Conventionally, silicon surface barrier detectors are used for alpha-particle spectroscopy. These typically comprises of a wafer of n-type silicon with a very thin gold contact evaporated on the front face and an aluminium contact evaporated on the back face. On exposure to oxygen a thin oxide layer forms beneath the gold layer which acts as a narrow p-type region. If this p-n diode is reverse biased very little current flows and a depletion region forms in the bulk of the device. In the depletion region, there is a very low density of charge carriers. Charges generated in the depletion region by action of ionising radiation are rapidly collected by the two electrodes and the device can be described as a solid state ion chamber. The thermally diffused p-i-n detector used in this experiment is similar to the silicon surface barrier detector just described. However, the contacts are generated by bombarding the surface of the silicon wafer with dopant ions rather than by thermal evaporation of metal contacts. The result is a slightly thicker contact, with a modified internal electric field distribution within the silicon wafer itself. The primary aim of this experiment is to investigate the properties of α-particles and their interaction with silicon pin detectors.

### 1.1 Theory

Alpha particles are helium-4 nuclei; two protons and two neutrons. They are highly ionising, have only a short range of a few centimetres in air, and have typical energies of about 5MeV if no other decay products are involved, although that varies depending on the radioisotope. For example, $^{212}$Po emits 8.78MeV alpha particles. The Geiger-Nuttall relationship describes how the energy of the alpha-particle depends on the half-life, mean life and decay constant [5]. The particle escapes from the nucleus by quantum tunnelling through the potential well of the nucleus [5]. This is shown in Fig. 1. The probability of quantum tunnelling depends on the shape of the barrier, particularly the height and width [6]. Even within the nucleus, the alpha particle is considered separate from the remainder of the nucleus; due to how tightly bound the alpha particle is [7]. Interaction between the alpha particle and the rest of the nucleus is made up of the strong nuclear force and the Coulomb interaction. The decay results from the repulsive Coulomb force overcoming the attractive strong nuclear force [7].

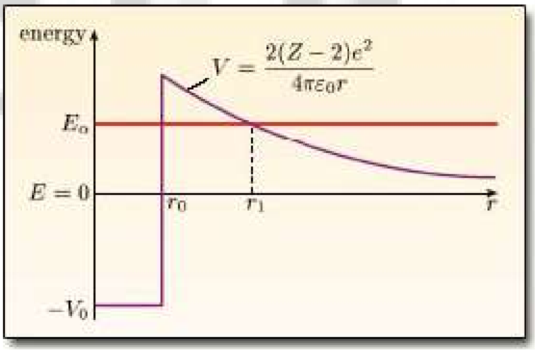

**Figure 1:** The potential well of a nucleus of atomic number Z, and an alpha particle [5]

Alpha particle energies can be detected using the deflection by electromagnetic fields, which was an early method of measuring the energy of charged particles [8]. Ionisation chambers and proportional counters have been used for this purpose. Semi-conductor detectors have also been developed, which have a much improved energy resolution over gas filled detectors, as well as higher intrinsic efficiency and fast responses. These, however, require cooling [2]. A thermally diffused p-i-n detector is used in this experiment, which is similar to silicon surface barrier detectors [8]. Silicon surface barrier detectors are made up of a wafer of n-type silicon, a thin gold contact evaporated on the front face, and an aluminium contact on the rear face. A thin oxide layer may form after exposure to oxygen, which will then act as a thin p-type region. An n-type region is doped with donor impurity atoms so that electrons are considered the charge carrier, while a p-type region has acceptor impurity atoms so that holes may be charge carriers [9]. If the p-n diode is reverse biased, a depletion region forms in which there is a very low density of charge carriers. Charges generated in this region by the ionising radiation are collected by the two electrodes [8]. The thermally diffused p-i-n detector differs in that it has contacts which are made by bombarding the surface of the silicon wafer. The resulting contacts are therefore slightly thicker, and the internal electric field distribution in the wafer differs as well [8, 10]. The absolute activity for a radioisotope can be found by using the total activity combined with a geometrical factor [11]. The count rate of the peak can be found, and it is assumed that each alpha particle which reaches it will be counted by the detector (100% intrinsic efficiency). So the absolute activity is defined by:

$$I = \frac{C_\alpha}{f} \times \frac{4\pi d^2}{A} \tag{1}$$

Where, I is the absolute activity, f is the fractional intensity of the alpha peak, $C_\alpha$ is the counting rate, d is the source detector distance, and A is the area of the detector active surface [8]. The Bethe-Bloch equation describes the stopping power of particles, defining the rate of energy loss per unit length:

$$S = \frac{kz^2\rho_e}{v^2}\ln\left(\frac{2mv^2}{I}\right) \tag{2}$$

Here, k is a constant, z is the charge on the ion, $\rho_e$ is the electron density of the absorber, $m$ is the electron mass, $v$ is the ion velocity, and I is the mean ionisation potential of the absorber atoms [8]. As this breaks down at low velocities, the following range equation is used for alpha particles.

$$R_\alpha = 0.318E_\alpha^{3/2} \tag{3}$$

Here, $E_\alpha$ is the energy of the alpha particle in MeV, and $R_\alpha$ is the range in cm of air where air is at standard temperature and pressure [8]. The total full-width-half-maximum (FWHM) can be described by the following equation

$$FWHM_{tot} = \sqrt{FWHM_{elect}^2 + FWHM_{stat}^2} \tag{4}$$

Here, $FWHM_{tot}$ is the measured peak width, $FWHM_{elect}$ is the width of an inserted pulser peak and $FWHM_{stat}$ is the width of the peak due to counting statistics [8]. As the pressure in the vacuum chamber increases, the alpha particle energy peaks widen. This is due to energy straggling, a process where statistical fluctuations occur in the number of collisions along the path of the particles and in the amount of energy lost per collision [12]. Energy straggling can be described by (5).

$$FWHM = 4.16(\Delta x)^{1/2} \tag{5}$$

Here, FWHM is in kev, and $\Delta x$ is the air-path thickness in mg $cm^{-2}$ [13]. The density of air can be found with the following equations:

$$\rho = \frac{P}{RT} \tag{6}$$

Here, p is the pressure in pascals, T is the temperature, and R is a gas constant which is equal to 287·05 J $kg^{-1}$ $K^{-1}$ for dry air [14]. From this, the range can be determined from the experimental result

$$R_\alpha = \rho \times d \tag{7}$$

This gives a range in mg $cm^{-2}$, and d is the source-detector distance [8].

## 2. Experimental Procedure

The triple alpha source ($^{239}$Pu, $^{241}$Am and $^{244}$Cm) was placed into a vacuum chamber containing the detector which is then evacuated. The source-detector distance is 1·0 ± 0·1cm. When a spectrum is taken, the main peaks are expected to be at 5155keV, 5486keV and 5805keV (for $^{239}$Pu, $^{241}$Am and $^{244}$Cm respectively in a 1·63kBq source) [8]. This was used to find the FWHM and the counting rate.

In the second part of the experiment, the detector was calibrated using the known energy peaks and using a pulser to inject a small charge into the pre-amplifier of known magnitude. The energy of the peak produced by the pulser is known, and can be reduced by a certain fraction so that the calibration can be extended to the lower channels of the multi-channel analyser (MCA). Equation (4) can be used to find the $FWHM_{stat}$ value from the resulting peaks. Equation (3) can be verified by changing the air pressure in the vacuum chamber and observing the change in energy of the alpha particles. Spectra are taken at 0, 200, 400, 600, 800 and 1000 mbar (or as close as it is possible to get to 0 mbar). By plotting graphs of peak energy against air pressure and FWHM against air pressure, the range can be found by extrapolating to zero and then using (6) and (7).

## 3. Results and Discussion

In the first part of this experiment, the FWHM of the main energy peaks is plotted against the peak energy as presented in Fig. 2. A Poisson distribution is assumed. This suggests that the energy resolution of the detector increases as the energy of those peaks increases.

The result of absolute activities for the radioisotopes comprising the triple alpha source using equation (1) is as presented in Table 1

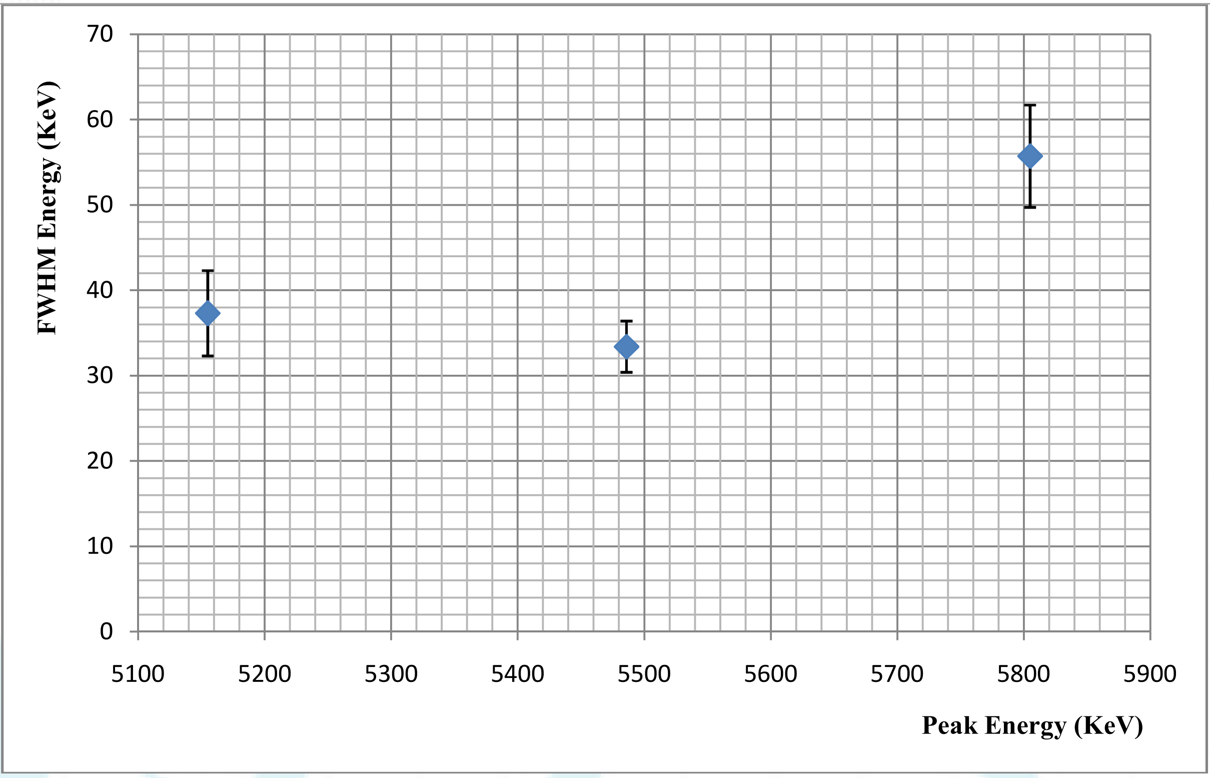

**Figure 2:** The full-width-half-maximum of the peaks produced by the triple alpha source against

**Table 1:** The absolute activities for the radioisotopes in the triple alpha source

| Radioisotope | Energy(keV) | Fractional intensity[7] | Absolute activity($s^{-1}$) |
|---|---|---|---|
| $^{239}$Pu | 5155 | 0.73 | 678·25±26·0 |
| $^{241}$Am | 5486 | 0.86 | 631·97±25·1 |
| $^{244}$Cm | 5805 | 0.73 | 146·08±12·1 |

In the second part of this experiment, (4) is used to find the $FWHM_{stat}$.The $FWHM_{tot}$ is from the $^{241}$Am peak, and $FWHM_{elect}$ is from the inserted peak. Hence:

$$FWHM_{tot} = \sqrt{{FWHM_{elect}}^2 + {FWHM_{stat}}^2}$$

$$= \sqrt{26.06^2 - 20.18^2} = 16.49\text{KeV} \quad (8)$$

The calibration uses an electrical peak inserted with a pulser at 5657·87keV. Peaks with values of one-half and one fifth of this are inserted so that the linearity of the response in the lower channels is the same as the higher channels. The peak energy against air pressure is as shown in Fig. 3. The lowest air pressure possible is 80. This shows a reduction in energy peak in the order of $^{239}$Pu > $^{241}$Am > $^{244}$Cm.

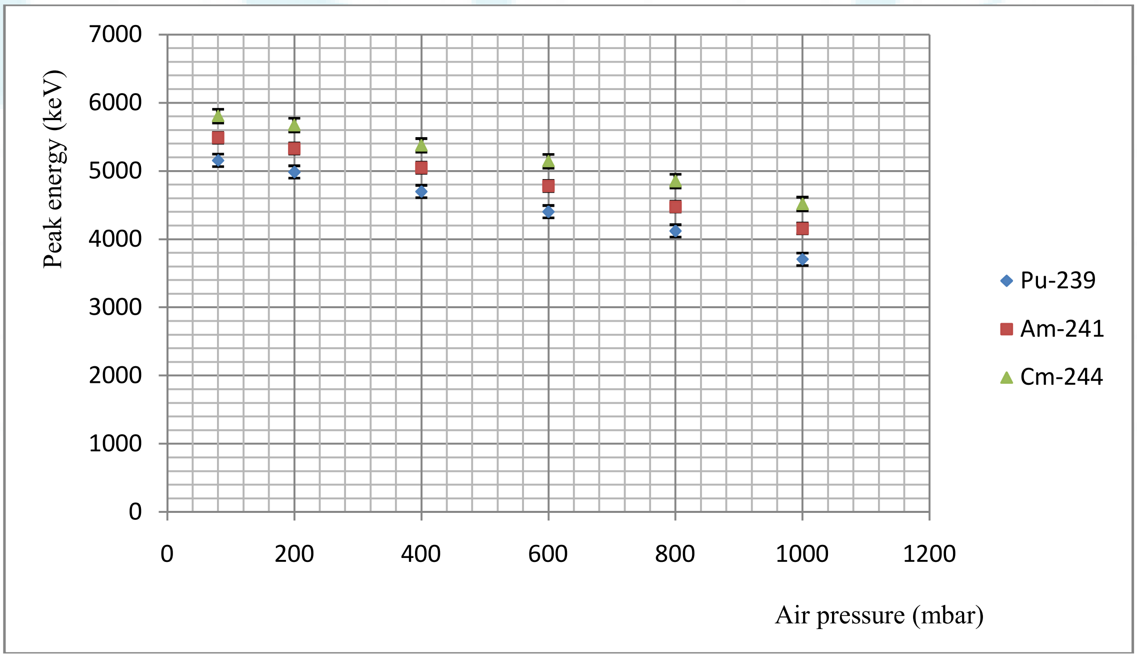

**Figure 3:** The Peak energy of the triple alpha source against the air pressure

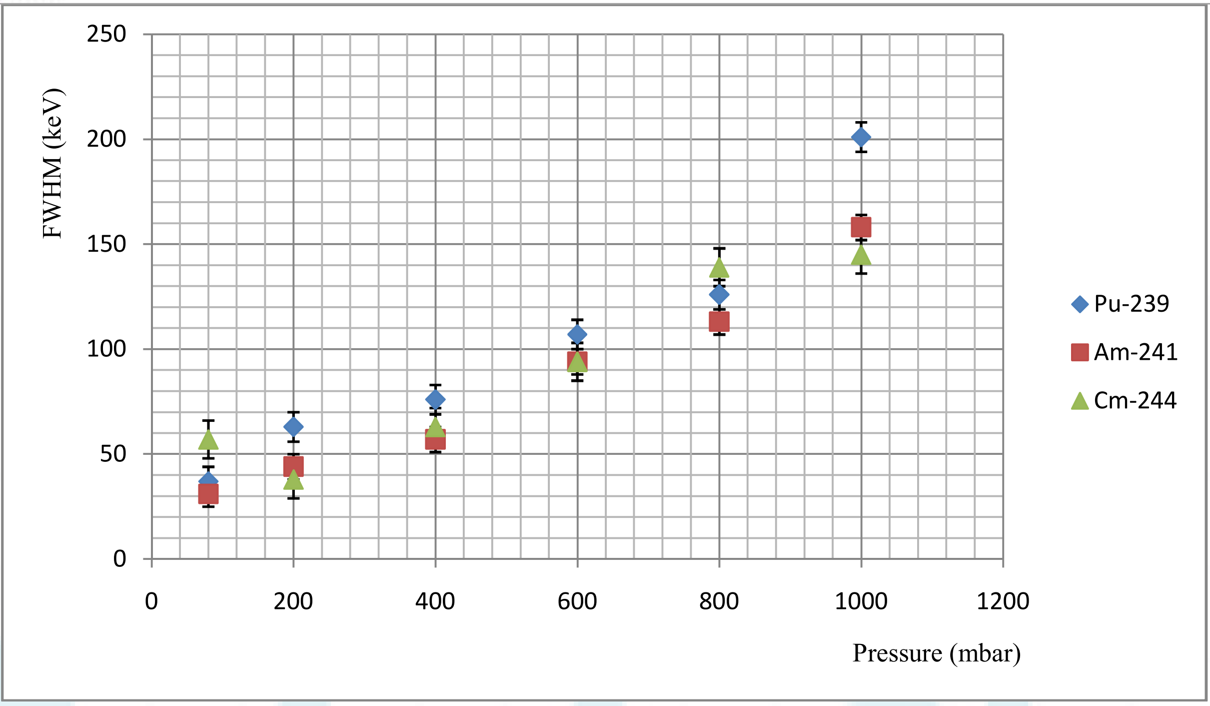

**Figure 4:** FWHMs of the triple alpha source against the air pressure

Fig. 4 shows the FWHM against air pressure when Poisson errors in the energy peaks are assumed. The FWHM of the $^{239}$Pu peak at 1000 mbar looks to be anomalous. The FWHM increases when the air pressure increases. This would be due to energy straggling, where statistical fluctuations occur in the number of collisions along the path of the particles and in the amount of energy lost per collision [12], and as there is a greater pressure in the chamber, more collisions would be expected. Using the equations from the spreadsheet program for the linear line fitted in Fig. 3, it is possible to extrapolate to where the energy of the peaks are equal to zero. This gives a pressure, which can then be converted into a density by (6), from which (7) can be used to find the range of the alpha particle. This can then be compared with (3). Poisson errors are assumed. The values from (3) fit well within the error ranges of the experimental results. Discrepancies can be accounted for as air is not an ideal gas, which (6) assumes.

STP is 273·15K and atmospheric pressure (101·325kPa) according to NIST [15].

**Table 2:** The alpha particle ranges, experimental and values obtained from equation (3)

| Radioisotope | Ra from equation (3) (cm in air at STP) | Ra from experimental results (cm in air at STP) |
|---|---|---|
| $^{239}$Pu | 3.72 | 4.29 ± 2.1 |
| $^{241}$Am | 4.09 | 4.90 ± 2.2 |
| $^{244}$Cm | 4.45 | 5.33 ± 2.3 |

## 4. Conclusions

In conclusion, alpha particle spectroscopy allows the identification of the nucleus from which an alpha particle is emitted as the energies are characteristic. Using the triple alpha sources: $^{239}$Pu, $^{241}$Am and $^{244}$Cm, it has been possible to measure a number of properties of the emitted alpha particles. These properties include the absolute activity of the $^{239}$Pu, $^{241}$Am and $^{244}$Cm sources, which are 678·25±26·0s$^{-1}$, 631·97±25·1s$^{-1}$ and 146·08±12·1s$^{-1}$ respectively. The ranges of the $^{239}$Pu, $^{241}$Am and $^{244}$Cm sources are found experimentally as 4·29±2·1cm, 4·90±2·2cm and 5·33±2·3cm respectively in air at STP, comparing favourably with the known values 3·72cm, 4·09cm and 4·45cm in air at STP. Also found was evidence for energy straggling, whereby as the air pressure increases, the number of collisions is likely to increase and, statistically, the amount of energy lost per collision varies, resulting in a broadening of the peaks. This experiment could be expanded by looking at lower energy alpha particles, to see if the relationship still holds, however for higher energies complications may be caused by nuclear reactions of the incident particles with the material of the detector [4].

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