Measuring energy loss of alpha particles in different vacuum conditions

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Abstract In this paper, energy loss of alpha particles in different vacuum levels is studied experimentally and *via* theoretical analysis. A better understanding of energy loss of α particle in vacuum will help detect more exact numbers of alpha particles. Two ^{239}Pu sources are used to measure the energy loss of α particle crossing different vacuum levels (different air pressures). The experimental data are obtained from an instrument – PAM-100 developed by authors. The experimental results have shown that increasing vacuum levels will lead to more alpha residual energy but less energy loss. When the vacuum level reaches 0.04 MPa, alpha particles (^{239}Pu, 5.115 MeV) will lose the energy of about 0.175 MeV with traversing 5 mm distance. Theoretical calculations have shown a good agreement with experimental results. This implies that the instrument has a high accuracy and could be applied in field work.

Key words Vacuum level, Alpha particle, Energy loss, ^{239}Pu

1 Introduction

Alpha particle detection plays an important role in radioactivity monitoring in nuclear facilities, and in their decommissioning and cleaning-up. This has motivated mechanism studies[1-9] on energy loss of *α* particles in matters. Alpha particles have a short range in air. The most energetic *α* particle (10.54 MeV) emitted from natural radioisotope travels 11.5 cm in air[1]. The fast energy losses of *α* particles result in a softening *α* spectrum with an apparent Gaussian edge having a dragging low-energy tail[9]. For minimizing the air effect, and improving the detection efficiency and energy resolution with a normal distribution, the sample chamber shall be evacuated. But still, the vacuum condition affects the spectral peaks, which may be partly broadened and shifted towards lower energies. As such a peak position means residual energy of the *α* particles, studying the vacuum effect on energy losses of alpha particles can help explain the peak-skew phenomena, which is of practical importance for field measurements.

Energy losses of *α* particles have been investigated by many scholars[1-15]. These efforts help better understand properties of *α* particles in different media. However, to the authors' knowledge, little experimental data on energy loss of *α* particles in different vacuum conditions are available, for checking the PAM-100 *α* particle measurement system developed in our lab. In this paper, energy losses of 5.115-MeV *α* particles from ^{239}Pu are measured under different vacuum conditions, and the data are compared with theoretical calculations. The comparison results verify the efficiency and reliability of the instrument.

2 Experimental

The experiments were carried out in China Academy of Engineering Physics. The PAM-100 system working principle is shown in Fig.1. It is a portable *α* spectrometer of 3-W power-consumption (less than 1 W for the counting unit), with an MCA of 1024 channels. An Au-Si surface barrier detector (GM40) of

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1200 mm^2, biased at 50 V, is used. The sample chamber is evacuated by a VBH2005 pump at pumping speed of 5 L/min, and the maximum vacuum is 0.02 MPa.

In the experiment, two ^{239}Pu α sources, in activities of 2.88×10^5 and 6.24×10^3 dpm (2π), were used. In the chamber, the source-to-detector placement was coaxial, at distance of 5 mm, with the source and detector facing to each other. The chamber was pumped to a predefined vacuum pressure of 0.04–0.09 MPa. The temperature was controlled at 25°C. In five minutes, an α spectrum could be obtained at each vacuum pressure.

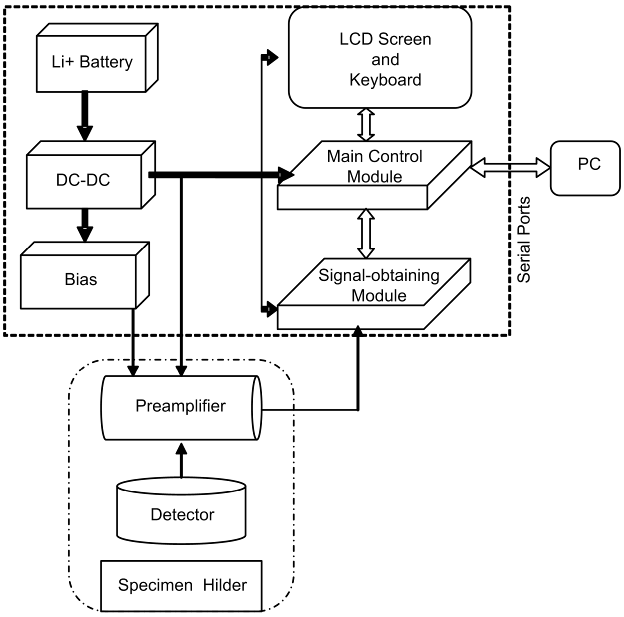

Fig.1 PAM-100 α particle measurement system working principle.

Alpha spectra of the two ^{239}Pu sources, and positions of the 5.115-MeV peak, were obtained at different vacuum pressures of 0.04–0.09 MPa (Fig.2). It can be seen that the number of counts increases with decreasing vacuum pressures, and the peak position moves rightwards, as an α particle loses less energy in higher vacuum. The spectra and peak positions from the two ^{239}Pu sources are qualitatively the same, despite the difference in number of counts and peak positions. As shown in the inserts in Fig.2, the peak positions at different vacuum pressures can be well fitted by a linear line.

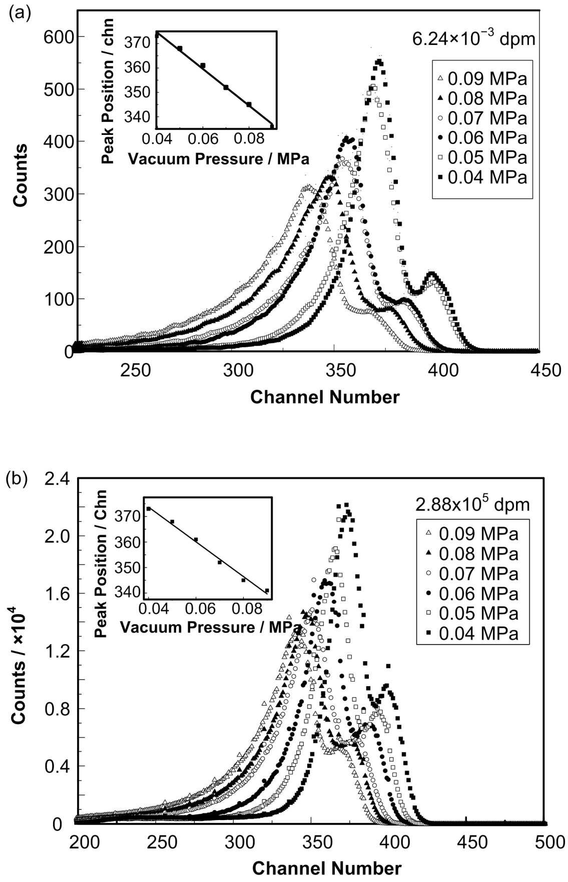

Fig.2 ^{239}Pu α spectra, and positions of the 5.115 MeV peak of ^{239}Pu as a function of the vacuum pressure (the inserts), at the source-to-detector distance of 5 mm, with the source activity of 6.24×10^3(a) and 2.88×10^5 dpm (b).

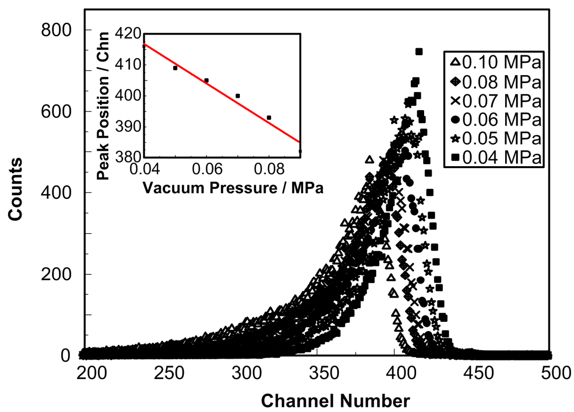

Fig.3 Alpha spectra and peak positions from a pure ^{239}Pu resource of 6.0×10^3 dpm at different vacuum levels (sdd=5 mm).

The two small peaks in the right to the normal peak positions in Fig.2 were caused by impurity in the ^{239}Pu sources, as was proved by another measurement with a pure ^{239}Pu source of 6.0×10^3 dpm, as shown in Fig.3.

3 Theoretical calculations

Alpha particles emitted from the source their lose energy before they reach the detector, due to their collisions with the residual air. Assuming that the atoms and orbit electrons act independently, and considering only energy loss to ionization and activation, the energy loss per unit distance (stopping power) of an α particle is given by Eq.(1)[10]

$$\frac{\mathrm{d}E}{\mathrm{d}x}=4\pi r_0^{\,2}z^2\frac{mc^2}{\beta^2}NZ\left[\ln\left(\frac{2mc^2}{I}\beta^2\gamma^2\right)-\beta^2\right] \quad (1)$$

where r_0 = 2.188×10^{-15} m is classical electron radius, and $4\pi r_0^2$ = 10^{-24} cm^2; mc^2 =0.511MeV is rest mass energy of the electron; $\gamma=(T+\mathrm{M}c^2)/(\mathrm{M}c^2)=1/(1-\beta^2)^{1/2}$, T is kinetic energy, M is rest mass of the particle, $\beta=v/c$, c≈3×10^{8}m/s is light speed in vacuum; N is number of atoms per cubic meter in the material through which the particle moves; $N=\rho(N_A/A)$, N_A is Avogadro's number (6.022×10^{23}/mol), A is atomic weight; Z is atomic number of the material; z is charge of the incident particle (z=2 for alpha); I is average activation potential of the material (I_N =97.8 eV, I_O = 115.7 eV)[10].

The energy loss of an α particle due to the residual air (in 21% O_2 and 79% N_2) can be calculated by Eq. (2):

$$\left(\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{air}}=0.21\left(\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{O}}+0.79\left(\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{N}} \quad (2)$$

The energy loss of α particle is proportional to the density of air, and Eq.(2) can be rewritten as

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{air}}=\left[0.21\left(\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{O}}+0.79\left(\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{N}}\right]\rho \quad (3)$$

where ρ is density of air in kg/m^3 in the sample chamber); $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{air}}$ is the energy loss per unit distance in MeV/m for alpha particles moving in air.

The equation between air density and vacuum is ρ_{air}= 11.69p − 0.00002[11]. Therefore, the α particle energy loss affected by vacuum conditions, $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{vac}}$, in MeV/m, can be given by

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{vac}}=\left[0.21\left(\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{O}}+0.79\left(\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{N}}\right]\rho_{\mathrm{air}} \quad (4)$$

where, p is vacuum pressure in MPa.

The stopping power for α particles from the ^{239}Pu source in vacuum can be is given as follows:

γ = (5.115−4×931.5)/(4×931.5) = 1.00137,

β = 0.00273.

Using Eq.(1), $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{O}}/\rho$ = 71.8 MeV·kg^{-1}·m^2; and $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{N}}/\rho$ = 75.6 MeV·kg^{-1}·m^2, where the O and N denote for oxygen and nitrogen, respectively;

Using Eq.(4), the stopping power of α particles in vacuum pressure of p can be calculated as

$$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{vac}} = 74.802\times(11.69\,p - 0.00002)\ \mathrm{MeV/m} \quad (5)$$

Then, energy loss of the α particles can be obtained by

$$\Delta E=\int_0^x\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{vac}}\mathrm{d}x \quad (6)$$

where ΔE=the energy loss of α particles passing through certain thickness(x) under different air pressures (p).

Table 1 shows the calculation results of the stopping power and energy loss by using Eq.(5) and Eq.(6). It can be seen that the energy losses decrease with the vacuum pressure. From the calculated energy loss of α particle emitted from the ^{239}Pu source in different vacuum conditions, we can compare the measured peak positions with the calculated residual energies of the 5.115-MeV α particle (Fig.4).

Table 1 Calculated stopping power and energy loss for α particles from ^{239}Pu in different vacuum conditions (sdd=5 mm)

Vacuum / MPa	Stopping power / MeV·m^{-1}	Energy loss (ΔE) / MeV
0.09	78.698	0.395
0.08	69.953	0.350
0.07	61.209	0.305
0.06	52.465	0.260
0.05	43.720	0.220
0.04	34.976	0.175

Figure 4 shows that both the α peak position measured by the PAM-100 system and the calculated residual energy have a linear relationship with the vacuum pressure, with a slope of about −20.0, and an intercept of around 1.8. The experiment results are in good agreement with theoretical analysis (R^2 = 0.9997 or 0.9882). This indicates that our developed alpha spectrometer PAM-100 has a higher accuracy and can be used in field work.

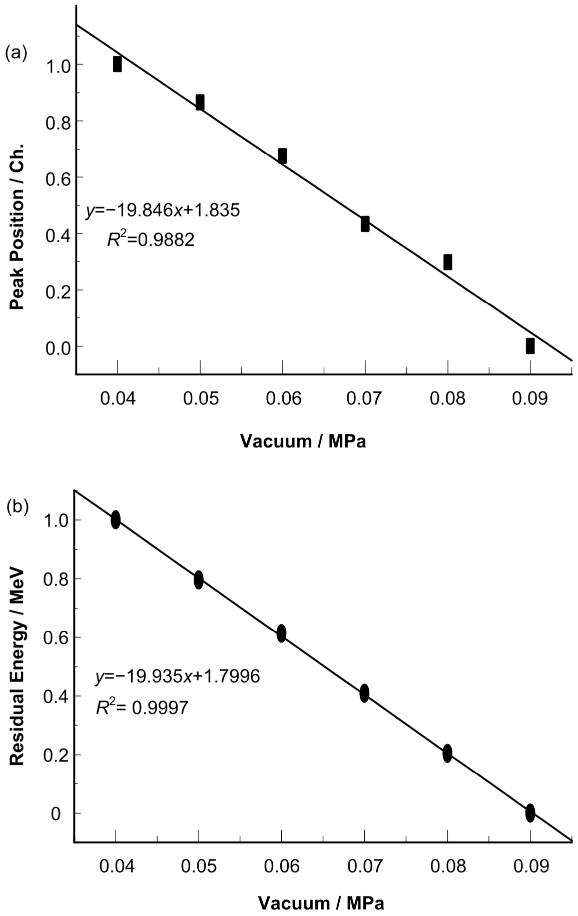

Fig.4 Alpha spectrum peaks and alpha residual energy curves affected by different vacuum conditions (normalized).

By combining the measurement and calculation results using the Matlab7.0 software, we could correlate the residual energy (E_i), peak position (Ch_i) and vacuum pressure (p) for 5.115-MeV α particles of ^{239}Pu by

$$E_i=4.9897-4.1562p+0.0003Ch+\mu_i \quad (=0,1,\cdots,n) \qquad (7)$$

where $p \in 0.01-0.1$ Mpa, and μ_i is random error of the model.

From statistics point of view, each measurement can be viewed as an independent event. According to the joint distribution theorem, if measurement A follows Gaussian distribution $N(\mu_1,\sigma_1^2)$, measurement B follows $N(\mu_2,\sigma_2^2),\cdots$, and experiment M follows $N(\mu_m,\sigma_m^2)$, then the joint distribution for independent measurements of A, B, ···, and M follows Gaussian distribution $N(\mu, \sigma^2)$, namely,

$$A+B+......+M \sim N(\mu,\sigma^2) \qquad (8)$$

The model in Eq.(8) can be used to plot the residual energy as a function of the vacuum pressure and α peaks in the spectra, which can be linearly fitted. By error analysis, the residual sum of squares (RSS) of the model is 0.000128, the unbiased estimation of variance of μ_i is 0.0000427. Therefore, one can use the mathematical model to know the residual energy (E) and peak position (Ch) of the 5.115-MeV α particles from a ^{239}Pu source in certain vacuum pressure (p). This can provide certain guides for spectrometer calibration in practice.

4 Conclusion

Different vacuum levels in the chamber will result in different energy losses for alpha particles. This paper has calculated theoretically the energy losses for alpha particles passing through certain distance under the different vacuum levels based on ^{239}Pu, 5.115 MeV. It shows a good agreement with experiment results. The experiment is performed using our developed alpha spectrometer PAM-100 which can be used in field work. A mathematical model for ^{239}Pu (5.115 MeV) is presented. By using this model, the residual energy as a function of vacuum levels and alpha spectrum peaks can be directly calculated. This study may help researchers calibrate portable spectrometers better and provide more parameters for field work.

References

1 Fu J. Research on long range alpha contamination instrument [D]. Chengdu University of Technology, 2008 (in Chinese).

2 Tuo X G, Li Z, Mu K L. J Nucl Sci Technol (supl), 2008, 45: 282–285.

3 Stella S, Bortolussi S, Bruschi P. Nucl Instrum Methods Phys Res Sect B, 2009, **267:** 2938–2943.

4 Kronenberg S, Brucker G J, Cummings B. Nucl Instrum Methods Phys Res Sect A, 2000, **454:** 520–527.

5 Rezentes P S, Romero J L, Castaneda C M. Nucl Instrum Methods Phys Res Sect A, 1995, **361:** 574–580.

6 Kohno T, Kiyota T, Matsufuji N. Nucl Instrum Methods Phys Res Sect A, 2000, **450:** 456–466.

7 Cruz S A. Nucl Instrum Methods Phys Res Sect B, 2004, **222:** 411–420.

8 Yu K N, Yip C W Y, Nikezic D. Appl Radiat Isot, 2003, **59:** 363–366.

9 Shi Z X, Zhang A M, Yao Q S. Calculation and experimental verification of alpha spectra under different

pressure, China Nuclear Information Centre, 2000.

10 Nicholas T. Measurement and Detection of Radiation, 2nd Edit [M]. University of Missouri-Rolla (USA), 1995, 146–149.

11 Yu Y C, Hsu J Y, Chen K M. Nucl Instrum Methods Phys Res Sect B, **266:** 1166–1169.

12 Diwan P K, Sharma V, Kumar S. Nucl Instrum Methods Phys Res Sect B, 2007, **258:** 293−298.

13 Pratibha T, Sharma V, Diwan P K, *et al.* Nucl Instrum Methods Phys Res, Sect B, 2008, **266:** 2556–2563.

14 Ammi H, Mammeri S, Allab M. Nucl Instrum Methods Phys Res Sect B, 2004, **213:** 60–64.

15 Ammi H, Zemith R, Mammeri S. Radiat Eff Defect Solids, 2006, **161:** 339–346.