An experiment to measure range, range straggling, stopping power, and energy straggling of alpha particles in air

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Experiments to measure range, range straggling, stopping power, and energy straggling of alpha particles are discussed in this article. Commercially available equipment with simple modifications is used for these measurements.

The study of the interaction of charged particles in matter attracted the attention of nuclear physicists immediately after the discovery of charged particles from radioactive sources. A clear understanding of the interaction was essential in designing radiation detectors and even in the measurement of the energy of these radiations through range measurements. The first theoretical work in this field was made by Bohr in 1913 even before he developed his theory of atomic structure.[1] Most of the experimental work using radioactive sources was also done on or before the 1930s.[2-4] There are several aspects to the study of charged particle interaction: measurement of range, the relationship between energy and stopping power, and the study of energy and range straggling. In this paper we discuss an experiment suitable for a senior nuclear laboratory to measure range, range straggling, stopping power, and energy straggling of alpha particles in air. The experiment uses a commercially available alpha spectroscopy system, a surface-barrier Si detector, and a modified vacuum chamber (ORTEC Model 807). Experiments to measure range and stopping power have been discussed by Heubner and Skolil[5] and Brendle *et al.*[6]

In the case of alpha particles produced by radioactive decay, in the energy range of 4–10 MeV, the medium usually used to study their interaction is air. These particles during their travel through air lose energy by collisions with atoms, and they eventually come to rest. The total distance an alpha particle travels in air, known as the range, depends on the rate at which it loses energy in the medium. This rate of energy loss, dE/dx, is called the stopping power. The latter decreases with increasing velocity. Hence one expects dE/dx to increase until the particle loses all its energy. However, this does not happen because of the random changes in the charge of the alpha particle due to the continuous capture and release of electrons, especially at lower velocities. The stopping power reaches a maximum around 1 MeV and then decreases.

Another quantity we looked at experimentally was the variation in energy transfer to the medium per unit distance, when monoenergetic alpha particles passed through the medium. Because of the variation in energy transfer, the alpha particle energy has a distribution known as straggling. Bohr[7] made the first theoretical study of this problem and concluded that the variance or the square of the standard deviation of the energy distribution of alpha particles after they have traveled a unit distance in a medium is directly proportional to the number of atoms in the path of the alpha rays. Livingston and Bethe[8] and Williams[9] later considered the effects of electron binding on collisions and showed that the variance is higher than estimated by Bohr for energies of alpha particles above 2 MeV. All of the above-mentioned theoretical discussions predict a Gaussian shape for energy distribution. However, Vavilov[10] and Haque and Hora[11] have shown that this is not necessarily true. References 8 and 11–14 are good reviews of these topics which the reader may find very useful.

Range and range straggling of alpha rays in air

In this experiment, a silicon surface-barrier detector is used for the detection of alpha particles. This detector is connected to a low-noise preamplifier (with a field-effect transistor at the input). The pulses from the preamplifier then go to an amplifier and scaler. Noise from the amplifier, after applying the recommended bias voltage, is found to be less than 0.05 V. To avoid counting the noise pulses, the discriminator of the scaler is set at 0.1 V.

The source and detector are kept in a modified vacuum chamber (ORTEC Model 807). The modifications made are (1) addition of a pressure gauge and (2) change of the direction of the vacuum valve so that the chamber can be isolated and kept at the required pressure. A differential pressure gauge (Wallace and Tiernan, Model FA 145) was used to measure the pressure inside the chamber. The smallest division on the gauge is 0.05 lb/in.^{2} and, therefore, we are able to take several readings, especially at the end of the alpha-particle range. In our experiment, the source, ^{241}Am electrodeposited on platinum foil, is kept in the vacuum chamber at a distance of 4.5 cm from the detector, which remained constant throughout the experiment. Instead of changing the source-to-detector distance, the

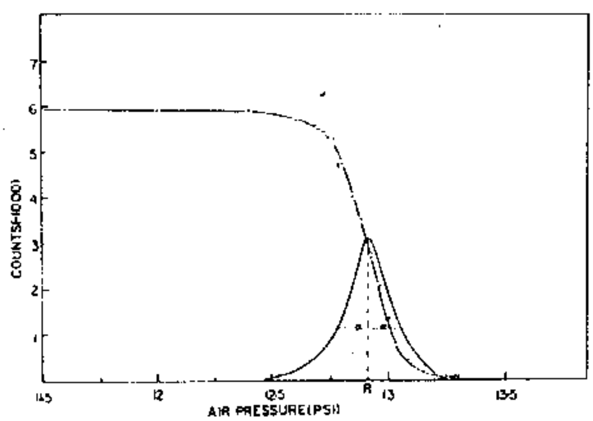

Fig. 1. Alpha counts as a function of air pressure. R, indicates the mean range. The bell-shaped curve is the number-range curve, and α is the range straggling parameter.

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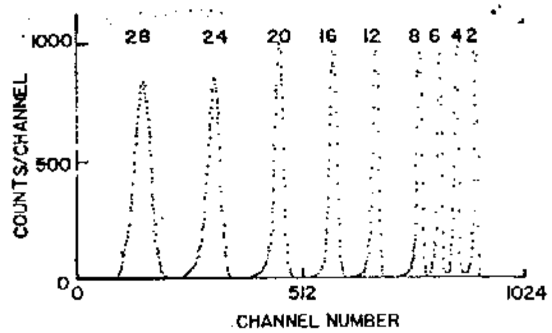

Fig. 2. Alpha spectrum as displayed on the multichannel analyzer for various pressures. Numbers on the top of the peaks indicate the pressure gauge reading for which the peaks were obtained. One division on the gauge is equivalent to 0.15 cm of air. The pulse-height distribution shown on the right (2) is for alpha particles that have traveled through an equivalent thickness of 0.3 cm of air.

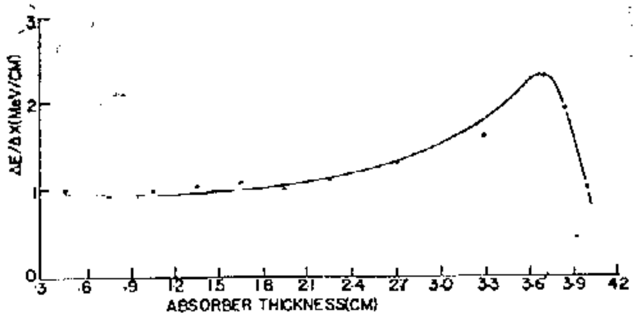

Fig. 4. Stopping power, dE/dx, as a function of absorber thickness.

amount of absorber between the source and the detector is changed by changing the pressure inside the chamber.

Alpha counts taken for various pressures are shown in Fig. 1. From Fig. 1 we obtain the mean range, where the counts decrease by half, as 4.15 cm at 25 °C with a possible error of 0.01 cm. This agrees with the reported values of range for 5.48-MeV alpha rays. The bell-shaped curve in Fig. 1 is obtained by taking the slopes of the range curve. This curve is known as the number-range curve, and its shape is Gaussian. From this curve we get the range-straggling parameter α as equal to 0.051 cm. ($\alpha = \sqrt{2}\, x$ standard deviation.) The value of α is expected to lie within 10% of 0.015X range,[15] that is, about 0.06 cm.

To obtain the relative stopping power as a function of energy, the pulses from the amplifier are fed into a 1024-channel multichannel analyzer to obtain the alpha spectrum at various pressures. The alpha peak, as displayed on the multichannel analyzer, moves to the low-energy side as the pressure inside the chamber increases (Fig. 2).

The procedures for analyzing the data are: (1) A Gaussian fit is obtained for each peak. (2) Peak positions in channel numbers are plotted for various pressures. (3) Extrapolating the peak position versus pressure curve to zero pressure, the peak position corresponding to no absorption in air is obtained. (4) A calibration, energy/channel, is obtained by dividing the energy of a ^{241}Am alpha ray (5.48 MeV) by the zero peak position. (5) Energies of the alpha peaks for various pressures are then calculated using this calibration.

Figure 3 shows a plot of energy of alpha rays as a function of the thickness of air (in cm). The stopping powers are calculated from this figure (we did not take the slopes; instead differences ΔE between each experimental point were calculated and divided by corresponding changes in absorber thickness, Δx). Stopping power as a function of absorber thickness is plotted in Fig. 4. The values of dE/dx agree with previously reported values in the 2-MeV region, but are slightly higher for lower and higher energies (5). The velocity dependence of the stopping power, increasing with decreasing velocity, is obvious from Fig. 4.

As mentioned earlier, energy straggling means variations in energy in a beam of energetic particles after passing through a certain amount of absorber. The increase in straggling is demonstrated as the increase in the width of the peaks as the alpha particles travel through increasing thickness of absorber (Fig. 2). The variance which is the square of the standard deviation per unit distance is a constant if the number of atoms per unit volume remains constant. The variance can be summed up for each increment. The resulting total variance will, therefore, increase linearly with absorber thickness, or in our experiment with pressure. Figure 5 is a plot of variance versus absorber thickness. The

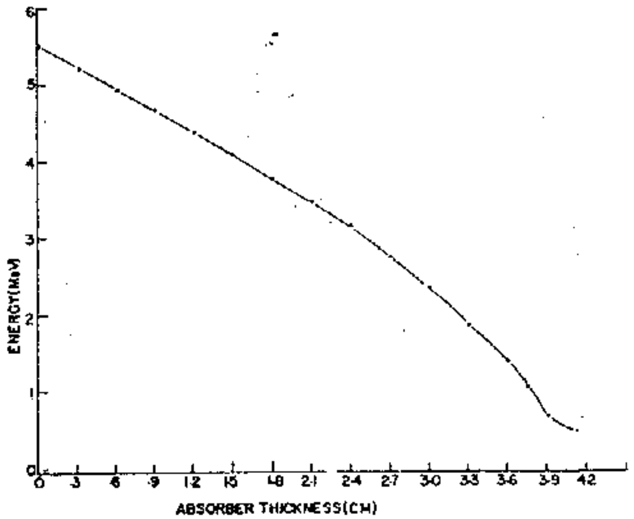

Fig. 3. Plot of energy of alpha rays as a function of the thickness of air (cm).

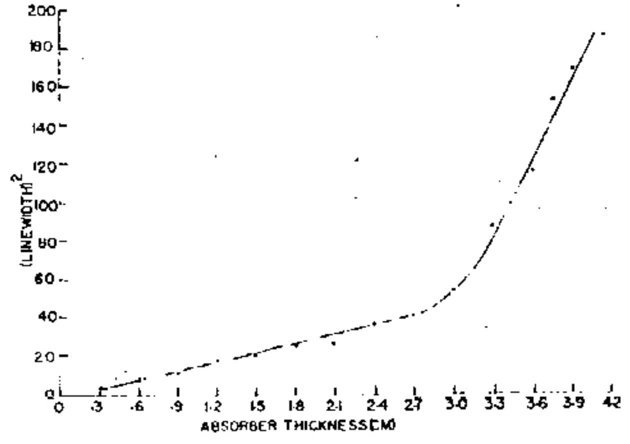

Fig. 5. Energy straggling as a function of absorber thickness. Square of the linewidth (linewidth is proportional to energy broadening) in channel numbers is plotted on the y axis. Also note that the energy of the alpha particle for 2.7-cm absorber thickness, where straggling increases rapidly, is about 2.47 MeV.

curve is linear up to an absorber thickness for which the energy of the alpha particles falls below 3 MeV. Beyond this point the variance increases rapidly demonstrating the need for some correction to Bohr's theory as suggested by Bethe[8] and Williams.[9] Such increase in variance has been observed in measurements of straggling in argon by Haque and Hora.[11]

Thus, by a simple modification, namely the addition of a pressure gauge to already commercially available equipment, we are able to study quantitatively important aspects of interaction of alpha particles with matter.

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