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Applied Radiation and Isotopes 59 (2003) 363–366

Applied Radiation and Isotopes

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Comparison among alpha-particle energy losses in air obtained from data of SRIM, ICRU and experiments

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Received 22 April 2003; received in revised form 9 June 2003; accepted 10 July 2003

Abstract

In the present work, we compare the alpha-particle energy losses in air obtained from experiments and from stopping powers given in Report 49 of the International Commission of Radiation Units and Measurements (ICRU49) and Stopping and Range of Ions in Matter-2000 (SRIM-2000). The alpha energy losses have been experimentally determined for both ^{241}Am and ^{230}Th sources using alpha spectroscopy; such losses are observed to deviate significantly from the calculated ones. The deviations suggested that the stopping powers given by SRIM-2000 might be too high and those given by ICRU might be even higher.

Keywords: Alpha energy; Stopping power; Air; Residual range; SRIM; ICRU49

1. Introduction

Stopping of energetic ions in matter has been a subject which has received great theoretical and experimental interest; the phenomena are usually characterized by the stopping powers. Stopping powers have been reviewed (e.g., Ahlen, 1980; Littmark and Ziegler, 1980; Ziegler, 1978, 1980; Ziegler et al., 1985). The most updated stopping powers in different media have been comprehensively given in Report 49 of the International Commission of Radiation Units and Measurements (ICRU49) (1993) and are also available in the software for the Stopping and Range of Ions in Matter (SRIM-2000) (Ziegler, 2001).

In the present work, we propose an indirect method to verify these stopping powers. We compare the alpha-particle energy losses in air obtained from data of SRIM, ICRU49 and experiments. In this method, measurements of stopping powers in air are replaced by measurements of alpha energies in air, the latter being much more convenient and usually achievable using laboratory alpha spectroscopy systems.

2. Experimental studies

The alpha sources employed in the present study were a planar ^{241}Am source (main alpha energy = 5.4857 MeV under vacuum, activity = 3.34 kBq, active diameter = 5 mm) and a planar ^{230}Th alpha source (main alpha energy = 4.6875 MeV under vacuum, activity = 662 Bq, active diameter = 5 mm). In the present investigations, the alpha energies were measured using an alpha spectroscopy system (ORTEC Model 5030). The alpha detectors are passivated implanted planar silicon (PIPS) detectors with areas of 300 mm^2. Energy calibration of the alpha spectroscopy system was carried out using these two alpha sources under vacuum. The alpha spectra were obtained by using a multi-channel analyzer with 2048 channels.

During the study of alpha energy loss in air, vacuum was not needed since the air was in fact required to cause

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doi:10.1016/S0969-8043(03)00201-X

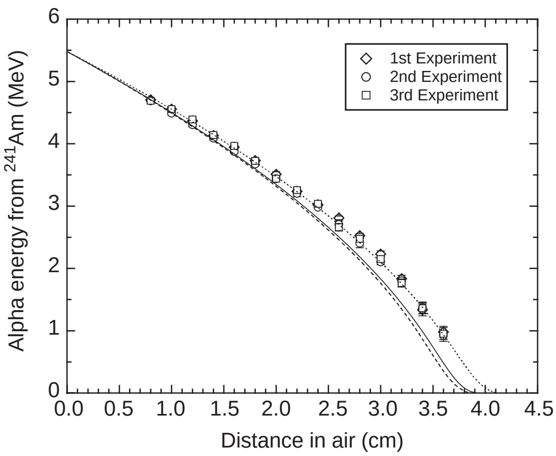

Fig. 1. Comparison between experimental data (three sets) for alpha energies from ^{241}Am in air as well as the calculations from ICRU data (dashed line), SRIM data (solid line) and SRIM data $\times$ 0.95 (dotted line).

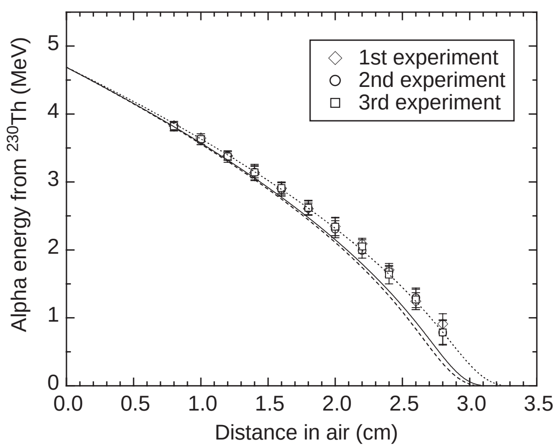

Fig. 2. Comparison between experimental data (three sets) for alpha energies from ^{230}Th in air as well as the calculations from ICRU data (dashed line), SRIM data (solid line) and SRIM data $\times$ 0.95 (dotted line).

an energy loss of the alpha particles. The air temperature was 22°C, the relative humidity was 65% and the air pressure was 1012 hPa. The alpha source was placed on a holder inside the chamber of the alpha spectroscopy system and was facing up towards the detector. A collimator made of acrylic resin with a size of 25 mm (L) $\times$ 25 mm (W) $\times$ 8 mm (H), and a hole at the center ($\varnothing$1 mm) was then placed above the alpha source to ensure that only alpha particles with nearly normal incidence were recorded by the detector. A ruler attached to the holder was provided with the alpha spectroscopy system to give the distance between the alpha source and the detector. Low-energy tails were very small and not readily observable in the present experiments.

The alpha energy losses in air were determined both for ^{241}Am and ^{230}Th sources. The results are shown in Figs. 1 and 2, respectively. Three sets of experimental data were obtained for each alpha source. For large alpha energies, the relative uncertainties in finding the peak alpha energies are very small, less than 1% for ^{241}Am and around 2% for ^{230}Th. For small alpha energies, the relative uncertainties become about 10% for ^{241}Am and around 20% for ^{230}Th. These uncertainties have been shown in Figs. 1 and 2. We can also see that the experimental data are very consistent among themselves.

3. Calculations from ICRU and SRIM

As mentioned before, stopping powers in different media have been comprehensively given by ICRU49 (International Commission of Radiation Units and Measurements, 1993) and by SRIM-2000 (Ziegler, 2001). The stopping power of particles in matter is usually given for different alpha energies E, so we write

$$-\frac{dE}{dx} = f(E). \tag{1}$$

From this we have

$$-\int_{E_0}^{E_x} \frac{dE}{f(E)} = \int_0^x dx = x, \tag{2}$$

where E_0 is the initial energy of the alpha particle and E_x is the energy of the alpha particle after traveling a distance x in air. This step is the most critical one in the present proposed method, since it transforms the measurements of stopping powers in air vs. alpha energy to the measurements of alpha energies E_x for different distances x in air.

We first employed the stopping powers provided in the ICRU49 report (International Commission of Radiation Units and Measurements, 1993). The linear stopping power of alpha particles in air were first fitted by the function:

$$f(E) = \sum_{i=1}^{5} a_i E^{b_i} e^{c_i E} \tag{3}$$

which gave the coefficients $a_1 = -14.42$; $a_2 = 17.05$; $a_3 = 207.4$; $a_4 = -87.89$; $a_5 = -130.5$; $b_1 = 0.4301$; $b_2 = 0.3222$; $b_3 = 0.5947$; $b_4 = 0.7725$; $b_5 = 0.5118$; $c_1 = -0.2149$; $c_2 = -0.1945$; $c_3 = -2.136$; $c_4 = -2.040$; $c_5 = -2.308$.

Fittings were carried out using the SigmaPlot® 5.0 software with iterations. The relative errors, defined as (ICRU–Fit)/ICRU, are shown in Fig. 3 as a function of the alpha energies, where ICRU refers to the ICRU49 data while Fit means the estimated value from the best fit to the ICRU49 data. One can see that most of the discrepancies are less than 1%, except for the largest

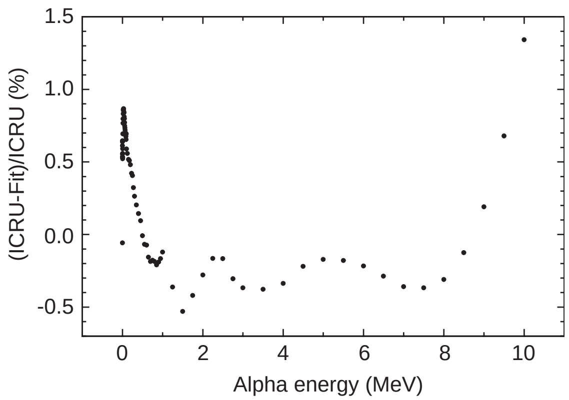

Fig. 3. Relative errors, defined as (ICRU-Fit)/ICRU, shown as a function of the alpha energies, where ICRU refers to the ICRU49 data while Fit means the estimated value from the best fit to the ICRU49 data.

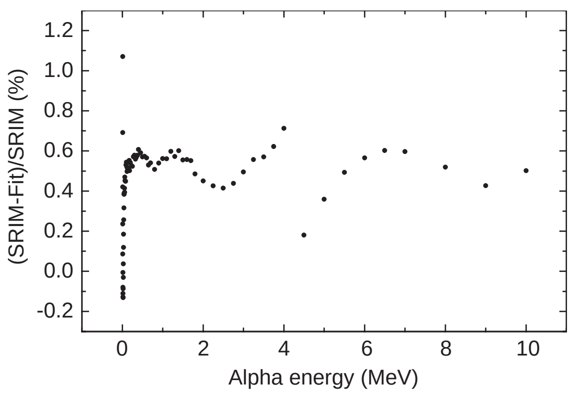

Fig. 4. Relative errors, defined as (SRIM-Fit)/SRIM, shown as a function of the alpha energies, where SRIM refers to the SRIM-2000 data while Fit means the estimated value from the best fit to the SRIM-2000 data.

considered energy of 10 MeV, which is in fact outside the energy range of our interest. By using Eq. (2), one can obtain the relationships between the distance x in air and the alpha energy E_x. These are plotted as the dashed lines in Figs. 1 and 2 for ^{241}Am and ^{230}Th, respectively.

We then employed the stopping powers provided by the SRIM-2000 (Ziegler, 2001), which calculated the stopping and range of ions (10 eV–2 GeV/amu) into matter using a quantum mechanical treatment of ion–atom collisions (the manual of SRIM refers to the moving atom as an "ion", and all target atoms as "atoms"). A full description of the calculation is found in the tutorial book written by Ziegler et al. (1985).

On the main menu of the SRIM-2000 software, the stopping and range table was selected. In this table, we selected "Helium" in the ion row and clicked "Compound Dictionary" to select "Air" to be the target. Finally, we clicked "Calculate Table" and a list of total stopping powers and estimates of the range for alpha particles in air was generated. These data were fitted using the function:

$$f(E) = \sum_{i=1}^{6} a_i E^{b_i} \exp(c_i E) \quad (4)$$

with the coefficients $a_1 = -10.1139$; $a_2 = 20.1723$; $a_3 = 208.1295$; $a_4 = -96.9209$; $a_5 = -128.8977$; $a_6 = -9.8901$; $b_1 = 0.3348$; $b_2 = 0.2940$; $b_3 = 0.5570$; $b_4 = 0.7475$; $b_5 = 0.4619$; $b_6 = 0.7501$; $c_1 = -0.5027$; $c_2 = -0.1973$; $c_3 = -2.8810$; $c_4 = -2.7620$; $c_5 = -3.0926$; $c_6 = -0.2455$.

Fittings were again carried out using the SigmaPlot® 5.0 software with iterations. The SRIM data required one more set of coefficients than the ICRU data to give a satisfactory fit. The relative errors, defined as (SRIM–Fit)/SRIM, are shown in Fig. 4 as a function of the alpha energies, where SRIM refers to the SRIM-2000 data while Fit means the estimated value from the best fit to the SRIM-2000 data. One can see that the discrepancies are always smaller than 1%, except for the lowest considered energy of 10 keV, where the discrepancy was 1.07%. Again, by using Eq. (2), one can obtain the relationships between the distance x in air and the alpha energy E_x. These are plotted as the solid lines in Figs. 1 and 2 for ^{241}Am and ^{230}Th, respectively.

4. Discussions and conclusions

From Figs. 1 and 2, the discrepancies between the experimental data and the calculations using ICRU and SRIM data are obvious, especially for large distances of air or for low alpha energies. The calculations from ICRU data and the SRIM data themselves also have some discrepancies, particularly in the low alpha energy region; these are due to the Bragg peak in the ICRU data being slightly larger than that in the SRIM data. However, these discrepancies are much smaller than those between the calculations and the experimental results.

An independent check of the discrepancies among the experimental data, the ICRU data and the SRIM data can be performed by looking at the inferred alpha-particle ranges in air, although it is not the objective of our experiments to determine alpha-particle ranges. A commonly used empirical formula (Kinsman, 1954) can be employed to estimate the ranges R in air (cm) for alpha particles with different energies E (MeV) as

$$R = 0.56E \quad (\text{for } E < 4\,\text{MeV}), \quad (5)$$

$$R = 1.24E - 2.62 \quad (\text{for } 4 < E < 8\,\text{MeV}). \quad (6)$$

For our alpha sources, ^{241}Am (alpha energy = 5.4857 MeV) and ^{230}Th (alpha energy = 4.6875 MeV), the ranges can be estimated to be 4.17 and 3.19 cm, respectively. However, from Figs. 1 and 2, the ranges are 3.9 and 3.1 cm, respectively, from calculations using ICRU and SRIM data. The shorter ranges might indicate that the stopping powers might be too large. For illustration purposes, we recalculate the relationship between the alpha energies and the distances in air by lowering the stopping powers given by SRIM by 5%; such curves are shown as dotted lines in Figs. 1 and 2. We see that under such a reduction of the stopping powers, the curves pass through the experimental data very satisfactorily. Furthermore, the ranges for alpha particles from ^{241}Am and ^{230}Th become 4.1 and 3.2 cm, respectively, which are very close to the values estimated by the empirical formula shown above in Eq. (6). The range for an alpha particle with energy of 5.4861 MeV was also given by Kaplan (1964) to be 4.109 cm, which is again very close to our value of 4.1 cm for ^{241}Am (alpha energy = 5.4857 MeV). The mean ranges in air (under STP) for alpha particles with energies 4.6875 and 5.4861 MeV were also given as 3.15–3.2 and 4–4.05 cm, respectively (US Department of Health, Education, and Welfare, 1970), which are again close to our values.

In the present paper, we have proposed a method for an indirect verification of the stopping powers based on alpha energy losses in air. By using this method, we have found that the stopping powers given by SRIM-2000 might be too high by 5%, and those given by ICRU might be even higher. The reasons are still unclear. If the stopping powers given by SRIM-2000 are reduced by 5%, the alpha energy loss in air will agree satisfactorily with the experimental data and will give ranges of alpha particles commensurate with those estimated by an empirical formula and with those found in the literature.

Acknowledgements

The present research is supported by the CERG grant CityU1081/01P from the Research Grant Council of Hong Kong (City University of Hong Kong reference no. 9040639).

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