Z DEPENDENCE OF 5–15-MeV ELECTRONS AND POSITRON RANGES

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The ranges of 5–15-MeV electrons and positrons are measured in substances having various atomic numbers (carbon, aluminum, sulfur, titanium, cobalt, nickel, copper, molybdenum, cadmium, and tungsten) using a Faraday cylinder. The dependence of the ratio R^+/R^- on Z of the absorber foil is calculated at 5, 10, and 15 MeV. The results indicate a slow growth of the ratio with the increase of Z. Our results are compared with other results in the literature.

1. INTRODUCTION

THE passage of electrons and positrons through matter is accompanied by elastic and inelastic collisions with nuclei and electrons of the medium, by energy loss through radiation, and by positron annihilation. The inelastic collisions include inelastic scattering of electrons and positrons on bound electrons of the slowing medium, and also the electrodisintegration of nuclei. Radiation losses are proportional to the square of the charge; therefore electrons and positrons in the 15–15-MeV range lose energy in light elements mainly through inelastic interactions, whereas in heavy elements the radiation losses are important.

McKinley and Feshbach[1] have shown that for $Z/137 < 0.2$ and $\beta \approx 1$ the cross section for fast electron scattering is given by

$$\sigma = \left(\frac{Ze^2}{2mc^2}\right)^2 \frac{1-\beta^2}{\beta^4} \sin^{-4}\frac{\vartheta}{2}\left[1-\beta^2\sin^2\frac{\vartheta}{2} + \pi\beta\frac{Z}{137}\left(1-\sin\frac{\vartheta}{2}\right)\sin\frac{\vartheta}{2}\right]. \quad (1)$$

The scattering cross section depends on the sign of the interaction potential; therefore in the general case the factor in square brackets is not identical for electrons and positrons. When Z is replaced by $-Z$, Eq. (1) describes positron scattering. The ratio σ^+/σ^- is smaller than unity, i.e., the positron scattering cross section is smaller than the electron scattering cross section at an identical energy and scattering angle. This ratio decreases as the scattering angle and the charge of the scattering nucleus are increased.

Experimental tests have confirmed McKinley and Feshbach's theoretical predictions, on the whole, with certain exceptions that we shall discuss. Most of the experimental investigations were performed with β particles at energies up to a few million electron volts. Seliger[2] investigated backward scattering of electrons and positrons as a function of Z; he obtained different backscattering coefficients for electrons and positrons. Herring et al.[3] measured the cross section ratio for electrodisintegration of different nuclei by electrons and positrons at energies up to 30 MeV; their results show that σ^-/σ^+ increases with Z.

It follows from the foregoing that positrons interact more weakly with matter than electrons having the same energy. Therefore positrons should lose less energy and have longer ranges.

Theoretical calculations of electron and positron ranges and their ratios are given in[4,5]. The ratio of the ranges increases slowly with Z. At ~ 2 MeV, R^+/R^- equals 1.06 for aluminum and 1.40 for lead.[5]

Somewhat unexpected results were obtained by Takhar,[6] who determined the ranges of positrons and electrons at ~ 2 MeV in different media and calculated their ratio. His work indicated that for $Z < 10$, $Z \sim 40$, and $Z \sim 60$–70 the range ratio differs very markedly from the theoretical values calculated in[5]; he obtained values up to 1.85 in the rare earth region, up to 1.3 for $Z < 10$, and up to 1.4 for $Z \sim 40$. It must be taken into account, however, that Takhar's results involve a considerable level of error, as was shown in[7].

Because of experimental difficulties the ranges of positrons having energies above 3 MeV were not measured.

We measured the ranges of electrons and positrons at 5, 10, and 15 MeV, and calculated their ratio as a function of the atomic number of the medium. The measurements were performed in carbon, aluminum, sulfur, titanium, cobalt, nickel, copper, molybdenum, cadmium, and tungsten.

2. EXPERIMENTAL APPARATUS

The source of high-energy electrons and positrons was the 30-MeV linear electron accelerator described in[8]. Positrons were produced in conversion targets bombarded by fast electrons; the technique is described in[9].

Figure 1 shows the experimental arrangement for determining electron and positron ranges in different media. The target was a tantalum plate 3.2 mm thick, which is 0.8 radiation length. For the purpose of having completely identical geometric conditions the electrons coming from the accelerator were sent through the same conversion targets. The resolving power of the analyzing magnet was 1.5% for 25-MeV incident electrons; the window width was 400 keV. The monitor was a plane-parallel ionization chamber. The diameter of the beam leaving the analyzer was 10 mm. The positron and electron currents transmitted through the absorbers were registered with a Faraday cylinder that was evacuated to $P = 3 \times 10^{-3}$ Torr. The charge collected by the cylinder was accumulated in a capacitor whose potential was measured with a U1-2 type electrometric d.c. amplifier.

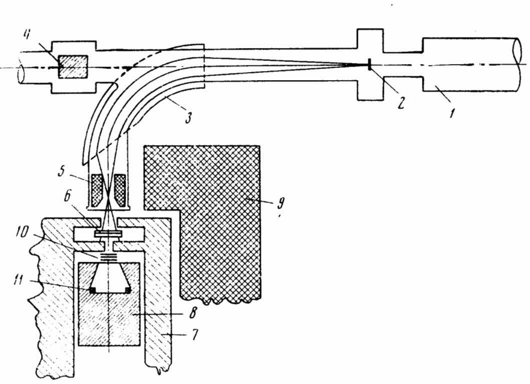

FIG. 1. Diagram of experimental apparatus for measuring positron and electron ranges. 1—accelerator exit tube, 2—target, 3—magnetic analyzer, 4—Faraday cylinder for measuring the intensity of electron current striking the target, 5—aluminum collimator, 6—monitoring ionization chamber, 7—lead shield, 8—Faraday cylinder for measuring particle currents transmitted through the absorber foils, 9—neutron shield, 10—foils, 11—permanent magnet (H - 300 Oe).

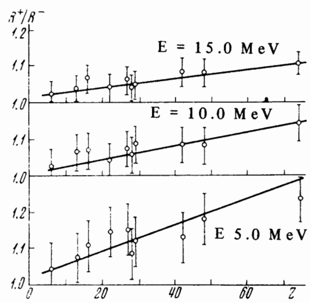

FIG. 2. Ratio of positron and electron ranges as a function of absorber atomic number (Z) for three particle energies.

To determine how data obtained with the described Faraday cylinder would be affected by an insufficiently high vacuum, we performed comparison experiments in which we also obtained data from a second cylinder located in the electron exit channel of the accelerator, at $P = 1 \times 10^{-6}$ Torr; this cylinder could be withdrawn from the beam. The discrepancy was at most 3% throughout the entire electron energy range.

We also determined the yield of secondary electrons from the entrance foil (~20 mg/cm²) of the Faraday cylinder. For this purpose a permanent magnet with a 300-Oe field was placed directly behind the entrance foil. This field was high enough to prevent secondary electrons from reaching the cylinder. The vacuum was insufficiently high to permit use of a screen grid. After the magnet had been removed without disturbing the vacuum in the cylinder the readings were compared; the differences were found to be at most 2%. This result permitted us to move the Faraday cylinder very close to the entrance foil, thus considerably increasing the solid angle of registration. Since the experimental geometry remained identical for the electron and positron range measurements, we were able to determine the range ratio very accurately.

3. ABSORBERS

The ranges of 5–15-MeV electrons and positrons in matter are of the order of a few g/cm²; therefore fairly thick foils were required. It was difficult to prepare the required samples, because industrial samples of technically pure elements have small dimensions. Nevertheless, in our investigations we were able to use technically pure samples of graphite, aluminum, sulfur, titanium, cobalt, nickel, copper, molybdenum, cadmium, and tungsten. All of these had diameters of at least 5 cm, which considerably exceeded the beam diameter. The individual foils varied in thickness from 0.1 to 0.5 g/cm²; thus enabling us to obtain very accurate transmission curves.

4. RESULTS AND DISCUSSION

We determined the ratios of extrapolated positron and electron ranges. Each extrapolated range was given by the point where the linear segment of the transmission curve intersected the abscissal axis. Each curve was plotted, as a function of particle energy, through points separated by intervals from 0.1 to 0.5 g/cm². The measurements of the R^+/R^- ratios are shown in Fig. 2. The errors of the ratios are 7% for 5-MeV particles, about 5% for 10-MeV particles, and 4% for 15-MeV particles.

The experimental results show that the ratio R^+/R^- diminishes as the particle energy is increased. This effect is accounted for by the fact that as the particle energy increases the total energy loss includes a decreasing relative amount of ionization loss and an increasing relative amount of radiation loss. The difference between the electron and positron ranges results from the ionization losses.

We must also mention that we observed no large difference between the positron and electron ranges in carbon and molybdenum, although Takhar obtained 1.29 for the ratio in carbon and 1.35 in molybdenum. The different techniques used by Takhar to measure the electron and positron ranges probably introduced a considerable error into his results, as has been stated by Cook.[7]

Our data agree well with Nelms' calculations[4] only for carbon and aluminum. At higher values of Z there is no agreement: the experimental values lie considerably above the theoretical results. This is accounted for by the fact that Nelms' calculations were performed only up to energies at which the radiation loss was at most 5% of the total loss. He thus took into account practically only the ionization loss. This limitation is quite inadequate for large Z and energies above 5 MeV.

Unfortunately, we were unable to compare electron and positron ranges at energies close to those used in Takhar's work, because our accelerator produced a very weak beam in this range. However, the range ratio at 5 MeV should not differ greatly from the ratio at about 2 MeV, because the radiation loss in a medium at 5 MeV is still not very high. We can therefore affirm that Takhar's results are in need of verification.

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