PHYSICAL REVIEW VOLUME 120, NUMBER 5 DECEMBER 1, 1960

Energy Loss Measurements for Heavy Ions in Mylar and Polyethylene*

PHILIP E. SCHAMBRA† AND ANDREW M. RAUTH
Department of Biophysics, Yale University, New Haven, Connecticut

AND

L. C. NORTHCLIFFE
Department of Physics, Yale University, New Haven, Connecticut

(Received March 22, 1960)

The energy loss of C^{12}, O^{16}, and Ne^{20} ions in passage through foils of Mylar and polyethylene has been investigated for incident ion energies of 10 Mev/amu and emergent ion energies in the region from 10 to 1 Mev/amu. The ion energies were measured with a magnetic spectrograph. The variation of emergent ion energy with absorber thickness (essentially the range-energy relation) is reported and compared with similar results for the same ions in aluminum. Within experimental error, the curves for Mylar and polyethylene differ from those for aluminum only in the scale of absorber thickness. For the same energy loss, the ratio of absorber thicknesses (in mg/cm^2) is 0.783 for Mylar to aluminum, and 0.692 for polyethylene to aluminum.

INTRODUCTION

IN the preceding paper[1] results have been presented which can be interpreted as a measurement of the range-energy relation for heavy ions in aluminum. Similar measurements with other absorbing materials are of interest not only for a better understanding of the energy loss process, but also because of the practical need to account for energy losses in counter windows, targets, etc., in experimental work with heavy ions. Organic foils often are used for such purposes. Moreover, a knowledge of the ranges and stopping powers for heavy ions in organic materials is of value to biophysicists in their attempt to interpret quantitatively the effects of ionizing radiations on biological systems.[2] Although some experimental information is available,[3–5] previous studies have been limited to ions of low energy[3] or to measurements in nuclear emulsions.[4,5] This paper reports measurements of the energy loss suffered by typical heavy ions (C^{12}, O^{16}, and Ne^{20}) in passage through foils of polyethylene and Mylar (polyethylene terephthalate).[6] The ions have fixed incident energies of ~10 Mev per nucleon and their emergent energies are measured as a function of absorber thickness. The results for Mylar and polyethylene absorbers are presented graphically and compared with the curves for the same ions in aluminum. Except for differences in the scale of absorber thickness, the curves for all three absorbers appear to be the same. Moreover, the absorber thickness scale conversion factors are in fair agreement with calculated stopping power ratios.

EXPERIMENTAL

Apparatus

Beams of heavy ions with kinetic energies of ~10 Mev/amu are produced by the Yale heavy-ion accelerator and held constant in energy by a magnetic analyzer. (The resolution of the analyzer was ±0.5% in this experiment.) A foil changer is used to place an absorber of known thickness in the path of the ions. The transmitted ion beam enters a magnetic spectrograph where its deflection is recorded on a strip of photographic film. The deflection is measured relative to a reference scale, a row of spots printed on the film at the time of exposure to the beam. The ion energy is calculated from the deflection. A detailed discussion of the spectrograph and the method of energy determination is contained in the preceding paper.[1] The discussion here will be limited to experimental features which are not common to both investigations, i.e., the absorbers, the energy resolution of the incident beam, and the technique by which the beam deflection was measured from the film strip.

Measurement of Absorber Thickness

The plastic absorbing materials were obtained commercially in the form of thin sheets, Mylar in (nominal) thicknesses of 1, 5, and 11 mils, and polyethylene in (nominal) thicknesses of $\frac{1}{2}$, 5, and 14 mils. A precision punch was used to cut circular foils $1\frac{1}{2}$ in. in diameter from the sheets. The average thickness of each foil (in mg/cm^2) was determined from its weight and area, and

---

* This investigation was supported in part by the U. S. Atomic Energy Commission and by funds provided under contract with The School of Aviation Medicine, U. S. Air Force Randolph Air Force Base, Texas.

† This investigation was carried out during the tenure of a Predoctoral Fellowship from the National Cancer Institute, U. S. Public Health Service.

[1] L. C. Northcliffe, preceding paper [Phys. Rev. **120**, 1744 (1960)].

[2] For a recent review of quantitative radiobiology, see papers by R. E. Zirkle, E. C. Pollard, T. H. Wood, and C. A. Tobias, in Revs. Modern Phys. **31**, 269 (1959). Some effects of heavy ions on various biological systems are discussed by J. L. Born *et al.* [Progr. in Nuclear Energy **2**, 189 (1959)]; G. Dolphin and F. Hutchinson [Radiation Research **13**, 403 (1960)]; and in abstracts of 1958 and 1959 meetings of the Radiation Research Society (Radiation Research **10** and **11**).

[3] See, for example, D. C. Lorents and E. J. Zimmerman, Phys. Rev. **113**, 1199 (1959), and J. P. Phelps, W. F. Huebner, and F. Hutchinson, Phys. Rev. **95**, 441 (1954).

[4] H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. **117**, 544 (1960).

[5] P. G. Roll and F. E. Steigert, Nuclear Phys. **16**, 534 (1960).

[6] The electron density of Mylar is within a percent that of dry protein and so one might expect these materials to exhibit similar stopping powers.

absorbers with a number of different thicknesses were obtained by combining selected foils into stacks. Each of the absorber stacks was mounted separately on one of the two foil holding wheels within the foil changer. By suitable manipulation it was possible to place any desired stack from one wheel in the path of the beam, alone or with any stack from the other wheel. Thus it was possible with eight absorber stacks of each material to obtain combined thicknesses which ranged from 0 to ~ 20 mils in steps of approximately 1 mil (≈ 3.4 mg/cm^2 for Mylar; ≈ 2.5 mg/cm^2 for polyethylene).

The accuracy of the absorber thickness assignments is limited by the uncertainties in the foil areas and weights, and by the uniformity of the plastic sheets. To minimize the uncertainty in the area of the thinnest foils, the plastics were placed between sheets of paper before they were punched and the foils which came from the punching process with poorly defined edges were discarded. In particular the edges of the thicker polyethylene foils appeared to be tapered, in places by as much as 3 or 4 mils. The Mylar foils in general were more cleanly cut than the polyethylene foils. Several foils of each thickness were flattened between pieces of glass and their diameters measured on a comparator. (Deviations from the punch diameter were more noticeable for polyethylene than for Mylar and largest for the thinnest foils.) For each thickness, the mean deviation from the average diameter was taken as an estimate of the uncertainty in foil diameter. Before they were weighed, the foils were washed with detergent, rinsed with distilled water, dried between lintless tissue, and desiccated for 24 hours. (The influence of the washing process on the foil weights was found to be negligible, as was the influence of atmospheric humidity.) Subsequently they were handled with blunted tweezers and lintless gloves. The weighing was done on a microbalance in an instrument room of controlled temperature, and the foils were allowed several hours to come to equilibrium in these surroundings before they were weighed. During the weighing, a beta source was placed near the foils to dissipate static charges. Each absorber stack was weighed twice, and each constituent foil was weighed independently. The uncertainty in the foil weight was estimated and added linearly to the uncertainty in foil area to give the over-all uncertainty in foil thickness. For polyethylene, the over-all uncertainties were $\pm 2\%$, $\pm 1\%$, and $\pm 0.5\%$ for the nominal $\frac{1}{2}$-mil, 5-mil, and 10-mil thicknesses, respectively, while for Mylar they were $\pm 0.4\%$ for the 1 mil, and $\pm 0.25\%$ for the 5- and 11-mil thicknesses.

The uniformity of the foils was not considered in arriving at the above uncertainty estimates. While the surfaces of the Mylar foils appeared smooth, the polyethylene foils were visibly scratched or striated. It was difficult to estimate the magnitude of these small scale irregularities. However, the large scale variations in the thickness of the plastic sheets were examined by noting the variations in weight among cleanly cut foils of identical area punched from the sheets in a square array. The variations were 3% or less over the Mylar sheets, but for polyethylene the variations were from 10% to 20% depending on the thickness of the sheet. The variations over the array were smooth rather than random functions of position, and were taken to represent a contour map of the sheet thickness. The foils used in the absorber stacks were punched from "plateau" areas. No attempt was made to estimate the added uncertainty in foil thickness caused by foil nonuniformity. However, the large number of foils used, their random orientation when stacked in the foil changer, and the large number of absorber changes during a run all should tend to reduce the influence of individual irregularities. The resultant errors are random and an upper limit for their magnitude is given by the scatter of the experimental data.

After the experimental runs the foil stacks were examined for physical changes caused by passage of the beam. Although no changes were observed in the thin foils, the thicker foils of both absorber materials were noticeably discolored. Moreover, the region of the polyethylene foils exposed to the greatest beam concentration had become transparent[7] and appeared to be slightly warped. However, an examination of the sequence of exposures made with these foils showed no indication of systematic change in their thickness. The foils were not reweighed after the experiments.

Measurement of the Ion Energy

The various charge states present in the beam were separated in the spectrograph and appeared as separate "spectral lines" on the film strip. The position of each line was measured relative to the reference scale also printed on the film strip. To facilitate this measurement the spectrum was projected onto a sheet of millimeter graph paper using a photographic enlarger. The magnification was adjusted to be exactly 10:1 by matching the projected reference scale to the lines of the graph paper. With this magnification the displacement of a sharp spectral line from the nearest reference scale spot could be determined within ± 0.05 mm. The position of an undeflected beam print relative to the same reference scale also was determined within ± 0.05 mm. The positions of the broad spectral lines observed with ions of low energy were measured by the densitometer-comparator method described in Sec. II-D of the preceding paper. From the measured deflection s, the quantity $\mathcal{E}_m$ (the kinetic energy per unit mass of the ion in Mev/amu) was calculated using Eq. (1) of the preceding paper:

$$\mathcal{E}_m=\left(1-\frac{1}{4}\frac{\beta^2}{1-\beta^2}+\cdots\right)\left(\frac{B_0}{K}\right)^2\left(\frac{Z}{m}\right)^2\cot^2\left(\frac{s}{a}\right),$$

---

[7] This has been previously observed for polyethylene. See, for example, C. D. Bopp and O. Sisman, Nucleonics **13**, No. 7, 28 (1955), for irradiation of polyethylene in a reactor.

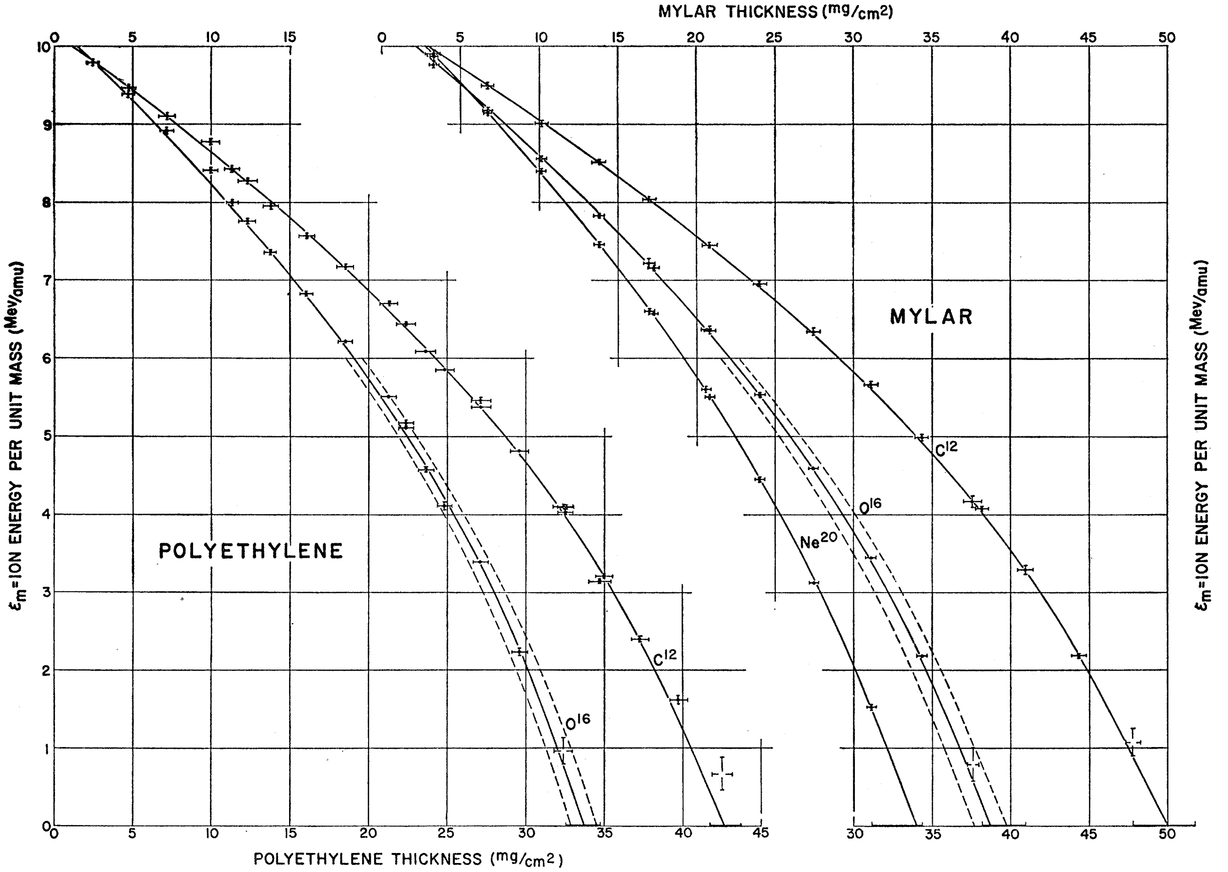

FIG. 1. The emergent ion energy plotted as a function of absorber thickness for C^{12}, O^{16}, and Ne^{20} ions in Mylar and for C^{12} and O^{16} ions in polyethylene. The ions all have initial energies of approximately 10 Mev/amu. The results may be interpreted as measurements of the range-energy relation for these heavy ions and absorbing materials. The vertical error bar associated with each experimental point shows the over-all uncertainty in emergent ion energy. The horizontal error bar represents the sum of the uncertainty in absorber thickness and the uncertainty in the incident ion energy (converted to an equivalent uncertainty in absorber thickness). The solid curves show the dependence of ion energy on absorber thickness as reported for *aluminum* absorbers (preceding paper), although the absorber thickness scale of the aluminum curves has been multiplied by a constant contraction factor to achieve the best fit to the present data. The contraction factor is 0.692 for the curves through the polyethylene data and 0.783 for the curves through the Mylar data. The dashed lines show portions of similar curves for contraction factors which differ from the above by $\pm 2\frac{1}{2}\%$.

in which Z and m are the charge and mass of the ion, B_0 is the magnetic field strength, β is the ion velocity, and K and a are constants of the spectrograph.

The estimated limit for *systematic* error in the spectrographic measurement of ion energy is $\pm 0.35\%$ (Sec. III, preceding paper). In addition, the inability to determine the exact position of a spectral line causes an uncertainty which varies smoothly from $\pm 0.4\%$ to $\pm 1.5\%$ as the ion energy decreases from 10 Mev/amu to 2 Mev/amu. The two energy uncertainties were combined by taking the square root of the sum of their squares, and the resultant taken to represent the over-all uncertainty in the energy measurement. Above 5 Mev/amu the resultant is approximately $\pm 0.5\%$, but for lower energies it is larger, increasing with decreasing energy. Most of the experimental points at energies below 2 Mev/amu have a considerably larger error caused by the overlapping of the spectral lines corresponding to different charge states. For each such point the error was estimated individually.

RESULTS AND DISCUSSION

The experimental data are presented graphically in Fig. 1. The solid curves superimposed on the data show (on an altered scale) the curves given in the preceding paper for the same ion beams in *aluminum* absorbers. The absorber thickness scale of the aluminum curves was contracted by the factor 0.692 to give the solid lines through the polyethylene data, and the factor 0.783 to give the solid lines through the Mylar data. The uncertainty in these contraction factors appears to be less than $\pm 2\frac{1}{2}\%$, as can be seen by the inferiority of the fit achieved with the dashed lines. It is noteworthy that within the experimental uncertainties of the data the contraction factor appropriate to each organic absorbing material appears to be independent of the identity and velocity of the ion. The implication is that the results obtained here can be supplemented by the results obtained in aluminum with other ions merely by application of the appropriate contraction factor to the aluminum results. Similarly, the stopping powers of Mylar and polyethylene for heavy ions can be found by suitable application of these factors to the stopping power curves for aluminum (Fig. 10, preceding paper).

If the contraction factor is independent of ion energy, it is given by the ratio of the stopping power of aluminum to that of the organic material. The stopping power ratio is the product of three terms: the ratio of stopping numbers, the square of the effective charge ratio, and the inverse ratio of the molecular weights. The effective charge of the ion can be determined from the equilibrium distribution of charge states in the emergent beam. This distribution is revealed by the relative intensity of the spectral lines corresponding to the various charge states. Charge state distribution measurements for O^{16} ions in aluminum are reported in the preceding paper. A spot check at ~ 2 Mev/amu and ~ 3 Mev/amu showed no significant differences in the charge state distribution for O^{16} ions in polyethylene. Thus the effective charge ratio is taken to be unity, and since the molecular weights are known the stopping power ratio (i.e., contraction factor) can be calculated from the ratio of stopping numbers. Various theoretical expressions give the stopping number in terms of the ionization potential of the absorbing material. Values of ionization potential are given by Bichsel[8] for aluminum and by Thompson[9] for the constituents of the organic materials. With these ionization potentials both the Bohr theory[10] and the Bethe theory[11] predict stopping power ratios which differ from the observed contraction factors by only a few percent. However the differences seem to be appreciably larger than the experimental error. In addition, the calculated stopping power ratios vary with energy, conflicting with the experimental observations. While the calculations have not been refined to account for nonparticipation of the K electrons in the absorbing material, the magnitude of this correction appears to be too small to explain the disagreement. Differences in the equilibrium charge distribution in the various absorbing materials also are too small to explain it. However, plausible changes of the ionization potentials used in the calculation might improve the prediction.

ACKNOWLEDGMENTS

The authors are indebted to Professor Franklin Hutchinson for suggesting the experiments with organic foils, to Dr. Geoffrey Dolphin and Fred Martin for assistance during and after the experiments, and to The Dow Chemical Company and E. I. du Pont de Nemours and Company for providing the polyethylene and Mylar. We also wish to thank Professor Robert Beringer for making the facilities of the Heavy Ion Accelerator Laboratory available to us.

---

[8] H. Bichsel, Phys. Rev. **112**, 1089 (1958).

[9] T. J. Thompson, University of California Radiation Laboratory Report UCRL-1910, August, 1952 (unpublished).

[10] N. Bohr, Phil. Mag. **25**, 10 (1913).

[11] H. A. Bethe, Ann. Physik **5**, 325 (1930).