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Henry Dakin and Roger Wallace

October 29, 1962

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INTRODUCTION

Presently available data on range energy and stopping power for heavy ions have been gathered together in order to provide a convenient source of information on which to base work on proposed heavy-ion accelerators. An additional motivation for this compendium is the growing interest in possible damage, by cosmic-ray heavy ions, to nerve tissue in astronauts making trips longer than a few weeks.

THE PASSAGE OF HEAVY IONS THROUGH MATTER

The first indication that ions heavier than protons are present in the primary cosmic radiation was secured from observations of wide, densely ionizing tracks in emulsions flown just below the top of the atmosphere (1). Since the Z of a particle can be identified by an examination of its track of developed silver grains in nuclear emulsion, it was soon realized that carbon, nitrogen, and oxygen, as well as heavier ions up to iron, were present in decreasing numbers with increasing Z.

In evaluating the behavior of a heavy ion in a stopping medium, it is of first importance to know the charge state of ion at any part of its path. This charge state is sually not single-valued, nor equal to Z. Furthermore, it changes with velocity. However, for a given velocity and density the change in charge state with different stopping mediums is quite small. The charge

state achieved should be thought of as the result of a competition between the loss and capture processes. The charge of any one ion fluctuates along its path, and eventually declines to zero as the end of the path is approached.

There is at present no rigorous theory that relates the velocity and charge state for a given ion in a given medium. An excellent review of the present theoretical situation has been given by Neufeld (2). There have been three basic approaches to the problem. The earliest is that of Bohr (3) and Lamb (4). It is assumed in the Bohr theory that an ion of large Z will lose all the electrons whose orbital velocities are less than its translational velocity through the stopping medium. This is certainly qualitatively true. Bohr argued that the slower and less firmly bound electrons are the most easily removed, and that in the inverse process electrons are more likely to be captured into orbits whose characteristic velocity is close to that of the moving ion through the medium.

Lamb stated the stripping condition in another way--that the moving ion is stripped of its outermost electrons until the ionization potential of the next stage of ionization is greater than the kinetic energy of electrons bombarding the ion with the velocity of translation of the ion through the medium.

In order to check the validity of the Bohr-Lamb criteria it is necessary to have values for the electron velocities in heavy ions. These have been given by the Bohr model (5), the Knipp and Teller model (6), and various refinements of the work of Lisitzin (7-11). The material pertinent to the heavy-ion problem from the last five references has been summarized by Neufeld (2, 12). At best, the experimentally measured values for the ionic charges as a function of velocity agree only roughly with those predicted from the theories of Bohr and Lamb. Furthermore, the species of the stopping medium and its density have not been considered at all.

Lassen has shown that in a gas fission fragments have a higher ionization in argon than in helium (13, 14, 15). On the other hand, Hubbard did not find this effect with either oxygen or neon passing through hydrogen, helium, nitrogen, or argon (16). It is possible that the effect is too small with oxygen or neon for him to have seen it. In a solid or a liquid, the effect of the stopping medium on the charge state of the traversing ion is less than in a gas. For fission fragments the variation is less than 10% in various media. Surprisingly, when nickel (Z=28) and Formvar (Z=4) are compared as stopping media, the stripping of heavy ions is greater in the Formvar (17, 18, 19).

The average charge of an ion increases with the pressure of a stopping gas, up to a plateau value. This effect depends on the relation average time between successive charge-exchange collisions relative to the average time for radiation of the ion in an excited state. If the collisions are infrequent, electrons that have been excited but not separated completely from the ion can radiate and drop back to their original state. If the collisions are closer together in time than the de-excitation processes, the electrons are successively excited and eventually removed from the ion.

It should be recognized that in an ion that is in equilibrium with its stripping medium, having been several times ionized and yet having several electrons remaining, the remaining electrons are not in their ground states, but are in a continual state of excitation. One of the inadequacies of heavy-ion theory is that the ions are actually in excited states whenever moving inside a medium, whereas all theories so far have been for ground-state ions. It would be desirable, in order to use the Bohr-Lamb theories in a solid or liquid, to know the distribution of electron oribital velocities or energies in an ion that is continually perturbed by collisions at a relatively

high frequency. Neufeld considers the effect of the moving ion on the medium, and the back reaction (due to rearrangement of the electrons of the medium) on the electrons of the ion (20). This refinement has the advantage of being applicable to any ion, whereas the Bohr theory is applicable only to heavy ions.

An alternative approach to the theoretical understanding of the passage of heavy ions through a medium has been suggested by Bell (21). He estimated the charge on a moving ion by considering the detailed balance of the capture and loss processes. Assuming that only one electron is lost or gained in any one collision, Bell has used, as the condition for equilibrium between a heavy ion and its medium,

$$\sigma_C(Z^*_{av}, v) \cong \sigma_L(Z^*_{av}, v) , \qquad (1)$$

where σ_C and σ_L are the capture and loss cross sections (for one electron) for an ion with average charge Z^*_{av}, and velocity v. The charges for fission fragments, computed on this basis by Bell, and the experimental values found by Lassen (13, 14) are shown in Table I. The modified values of Lassen shown in the table are corrections made by Bell for a 6% momentum difference between Lassen's measurements and Bell's calculations. This method has been refined by Gluckstern (22), who instead of using for σ_C the sum of individual capture cross sections into the various states available has used the capture cross section for any electron. This decreases the value of the cross section by about 40%. In addition, Gluckstern modified the Bell statistical model so that it would apply to light ions in which there are too few electrons for a statistical model. This was done by substituting for the Thomas-Fermi distribution one in which the electrons are located in concentric shells with radii corresponding to the known ionization potentials.

The capture and loss cross sections calculated by Gluckstern (22) for oxygen, neon, phosphorus, and argon as functions of velocity are shown in Figs. 1-4. The calculated charge distribution on oxygen and neon ions in argon compared to the experimental values of Hubbard (16) are seen in Figs. 5, 6 for two different energies. It is seen that the agreement is good. The gradual increase in average ion charge with increasing velocity is compared with the experimental results of Reynolds, (17, 18, 19), Stephens (23), and Hubbard (16) in Fig. 7. The agreement between theory and experiment is seen to be better than 1/2 of a charge state in all cases.

The build-up of the +3, +4, +5, and +6 charge states of 8.7-MeV oxygen ions in argon as experimentally measured by Hubbard (16), is seen in Fig. 8. The solid lines in Fig. 8 are least-squares fits to the experimental data, not the theoretical values. Gluckstern (22) had used these values and, for example, the rate of loss of +4 ions with depth is given by

$$\frac{dN_4}{dx} = -\sigma_{43} N_4 - \sigma_{45} N_4 + \sigma_{34} N_3 + \sigma_{54} N_5 . \qquad (2)$$

From this relation one can obtain the experimental cross sections given in Table II for comparison with the theoretical values from Fig. 1. The agreement is good, except that the measured capture cross sections for low-charge states are smaller than those calculated.

In view of the fair success of the capture-and-loss model, the following conclusions from it are of interest.

a. The capture cross section is independent of the particular ion, and is proportional to $Z^{*2}/V^{3.5}$.

b. The loss cross sections have maxima and are sensitive to the model of ion used.

c. The charge distributions do not change much in width with velocity.

d. The average charge is independent of the stripper material.

e. The average charge increases with velocity until the K shell begins to ionize, and then levels off.

f. Possibly double- and triple-ionization cross sections and capture cross sections should be included in this analysis.

There are indications that the double-ionization process may be as much as 50% of the single-ionization processes. This would force a modification of the theoretical cross sections for single events given in Figs. 1-4.

Some of the above features are illustrated in the experimental charge distributions for oxygen and neon measured by Hubbard (16) and shown in Figs. 5 and 6. Additional detailed experimental work with results parallelling those given in Figs. 5, 6, and 8 is described by Nikolaev (24).

RANGE-ENERGY AND STOPPING-POWER DATA

Many experiments have been conducted to measure the ranges of heavy ions of different energies in a variety of materials. The authors (references 25-30) who have reported on these experiments have not all plotted their data in the same way, some preferring, for example, range vs energy, others preferring E/A vs range, and still others condensing the range by multiplying it by Z^2/A of the heavy ion, and plotting this either as the independent or the dependent variable. Because of the practical usefulness of this information, the curves given in Figs. 9-19 have been replotted wherever this was necessary to give consistent data. Ranges for all materials, except emulsion, are given in units of mg/cm^2. Ranges of ions in emulsion are given in microns. Energies, in all cases, refer to total ion energy, rather than to energy per nucleon (E/A).

Somewhat less information is available on stopping power as a function of range or energy or velocity. Here, too, one finds considerable variety in the way in which data prepresented by different authors. Accordingly, Figs. 20 through 28 have been replotted to give stopping power as dE/dx (MeV/micron) for ions in emulsion, and as $dE/\rho dx$ (MeV $mg^{-1}cm^{2}$) for ions in all other materials. The very extensive work on tissue by Neufeld and Snyder (31, 32), shown in part in Figs. 26 and 27, should be especially noted, since this is the basis for the biological evaluation of the effects of heavy ions.

Additional specalized curves for heavy ions which may be of use in special applications are given in Fig. 28 from Roll and Steigert (28), which shows dE/dx vs energy in emulsion, Fig. 29 from Heckman (29), which shows dE/dx vs residual range in emulsion, Fig. 30 from Simons (33) for the number of ion pairs formed per μ in H_2O vs the residual range in H_2O, and Fig. 31 from Brustad (34) for the experimental Bragg peaks of B, C, O and Ne in tissue.

Accelerator Studies

The present accelerators can give monoenergetic, intense beams of ions with Z as high as 18. It is possible to quickly change from one ion to another, which is very convenient experimentally and perhaps reduces some systematic errors.

CONCLUSION

At present the physicist has a fair theoretical understanding of heavy ions. The technology for producing them and accelerating them is well developed, although the maximum energies now available are disappointingly small. One area in which there is little or no information available is neutron production by heavy ions as a function of energy and of A. Biological experiments indicate that effects produced by heavy ions are quite different from those of x rays.

There is a prospect of gaining valuable new information in the bioradiology of heavy ions through the use of experimental factors, such as variable radial charge distribution, that are not possible with presently available radiation sources. This prospect argues strongly for early construction of new heavy-ion accelerators of high energy.

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Table I. Charges of fission fragments obtained by Bell (Ref. 21) and by Lassen (Refs. 13 and 14).

Stopping medium	Ion species	Measurements by Lassen	Modified values from Lassen	Values calculated by Bell
Hydrogen	Light fragment	15.8	16.7	22.5 (21)
	Heavy fragment	12.6	13.3	16.3 (15)
Helium	Light fragment	14.1	14.9	16.5
	Heavy fragment	11.6	12.2	12.5
Oxygen	Light fragment	15.2	16.1±0.5	15.5
	Heavy fragment	14.1	14.8±0.5	13.5

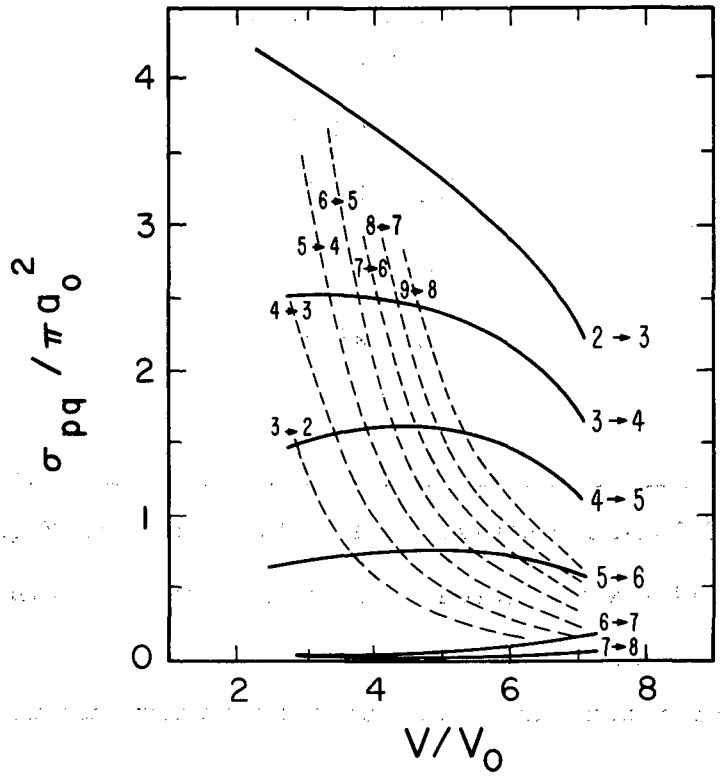
Table II. Comparison of experimental and theoretical cross sections for 8.7-MeV oxygen ions ($V/V_0 = 4.7$) in argon. (From Gluckstern, 1954.)

$p \rightarrow q$	Experimental[a, b] $\sigma_{pq}/\pi a_0^2$	Theoretical[c] $\sigma_{pq}/\pi a_0^2$
$3 \rightarrow 4$	2.27 ± 0.1	2.65
$4 \rightarrow 5$	1.77 ± 0.15	1.75
$5 \rightarrow 6$	0.81 ± 0.2	0.80
$4 \rightarrow 3$	0.14 ± 0.1	0.65
$5 \rightarrow 4$	0.57 ± 0.15	0.95
$6 \rightarrow 5$	1.22 ± 0.2	1.30

a. Determined from a least-squares fit to the data in Fig. 5.

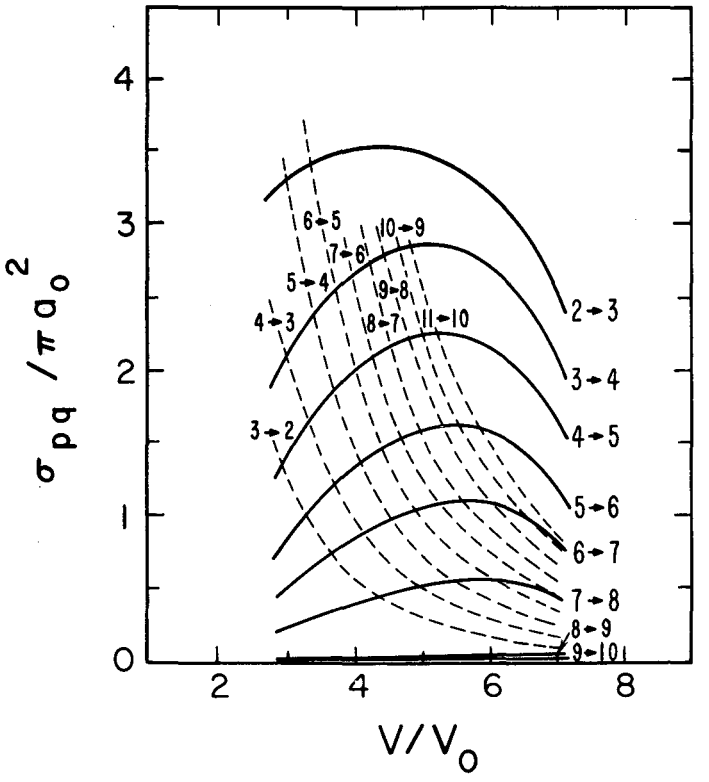
b. Errors listed are estimated from the uncertainty in the data.

c. Obtained from Fig. 1.



MU-29274

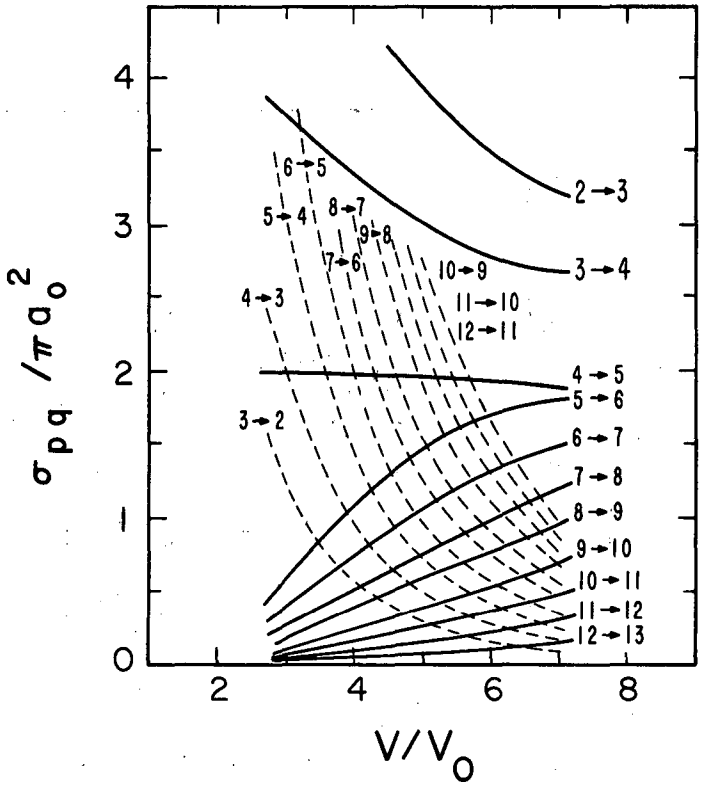
Fig. 1. Modified capture cross sections (-----) and modified loss cross sections (——) for oxygen ions in argon (Z_2=18).
$V_0 = c/137 = 2.18\times10^8$ cm/sec;
$a_0 = h/me^2 = 0.53\times10^{-8}$ cm;
$\pi a_0^2 = 8.8\times10^{-17}$ cm^2.
(From Gluckstern, 1954.)



MU-29275

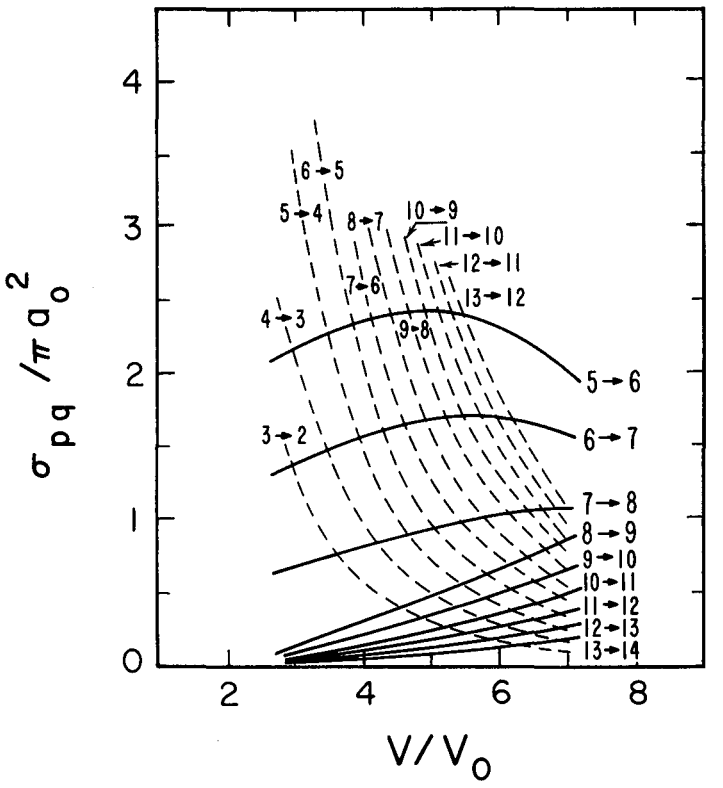
Fig. 2. Modified capture cross sections (-----) and modified loss cross sections (———) for neon ions in argon (Z_2 = 18).

(From Gluckstern, 1954.)



MU-29276

Fig. 3 Modified capture cross sections (-----) and modified loss cross sections (——) for phosphorus ions in argon (Z_2 = 18). (From Gluckstern, 1954.)



MU-29277

Fig. 4. Modified capture cross sections (-----) and modified loss cross sections (——) for argon ions in argon (Z_2 = 18).
$V_0 = c/137 = 2.18\times10^8$ cm/sec;
$a_0 = h/me^2 = 0.53\times10^{-8}$ cm;
$\pi a_0^2 = 8.8\times10^{-17}$ cm^2.
(From Gluckstern, 1954.)

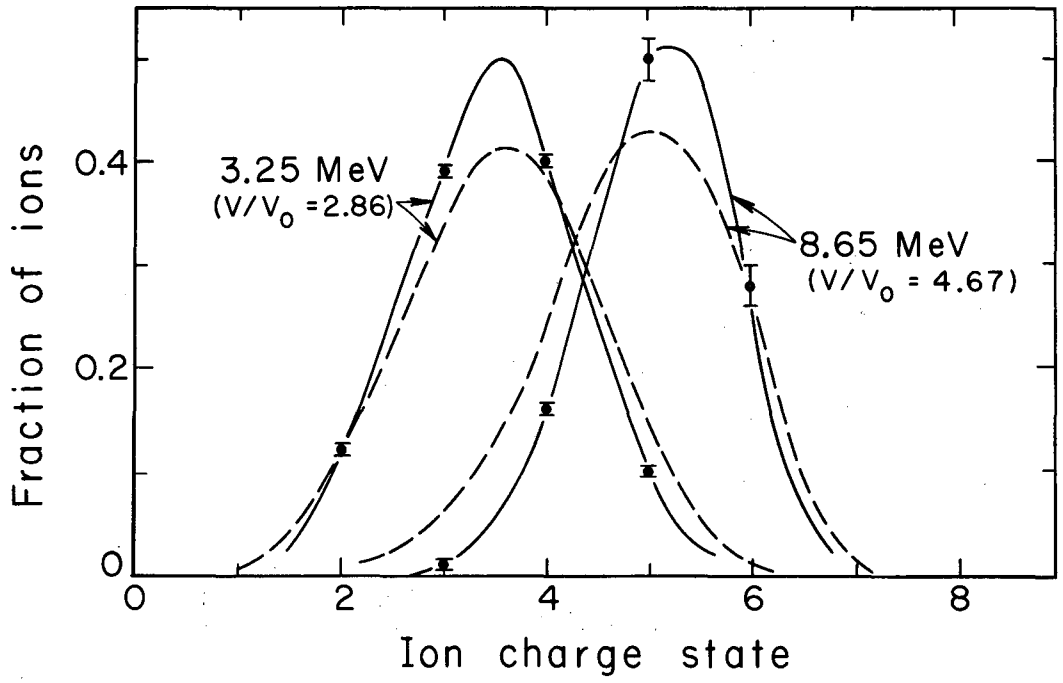


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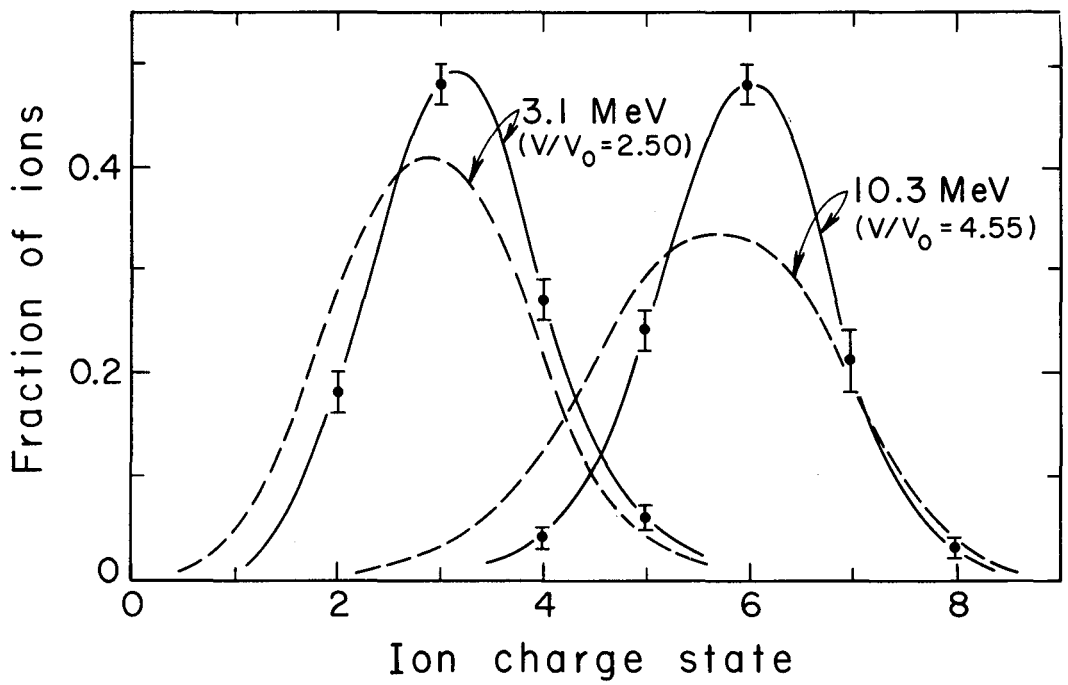
Fig. 5. Charge distribution at equilibrium for oxygen ions in argon.

(From Gluckstern, 1954.)
----- modified theory
experimental values



MU-29279

Fig. 6. Charge distribution at equilibrium for neon ions in argon.

(From Gluckstern, 1954.)

----- modified theory

⊥ experimental values

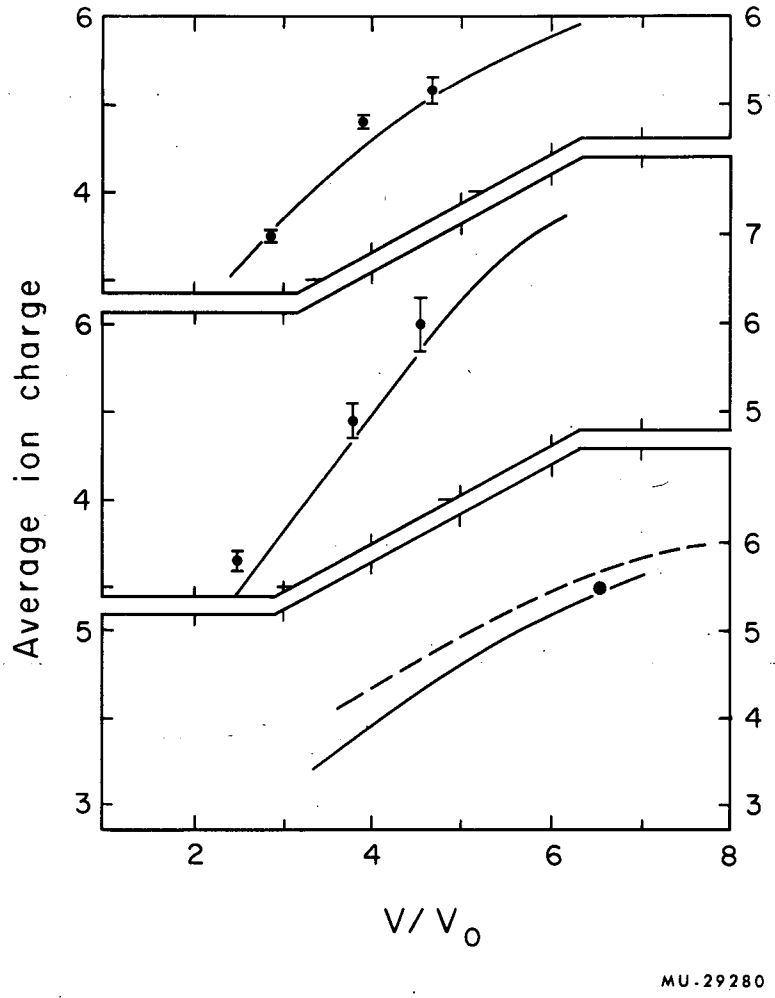
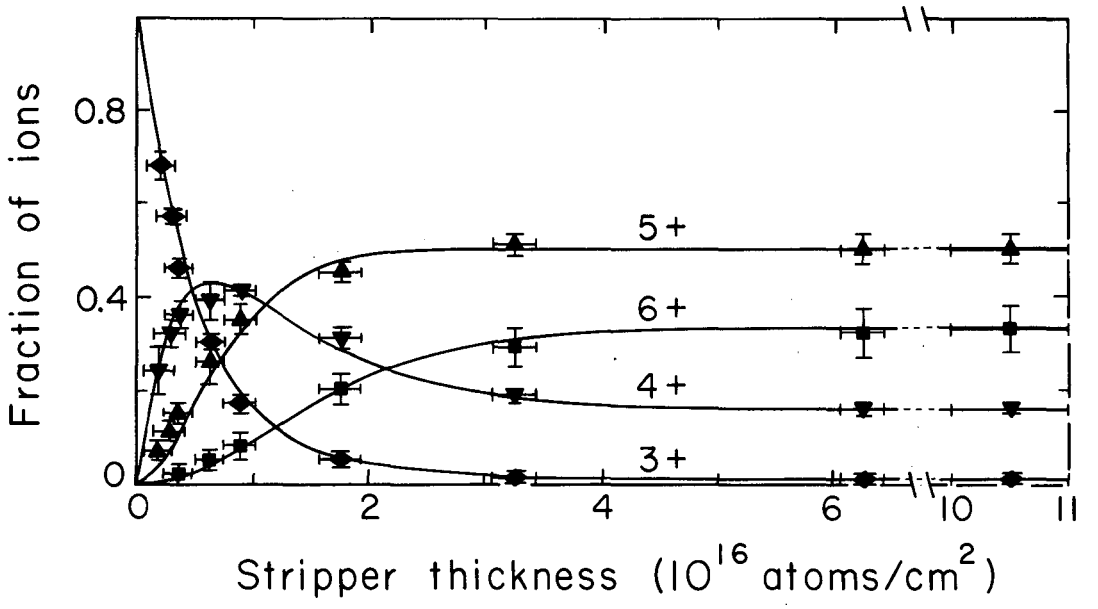
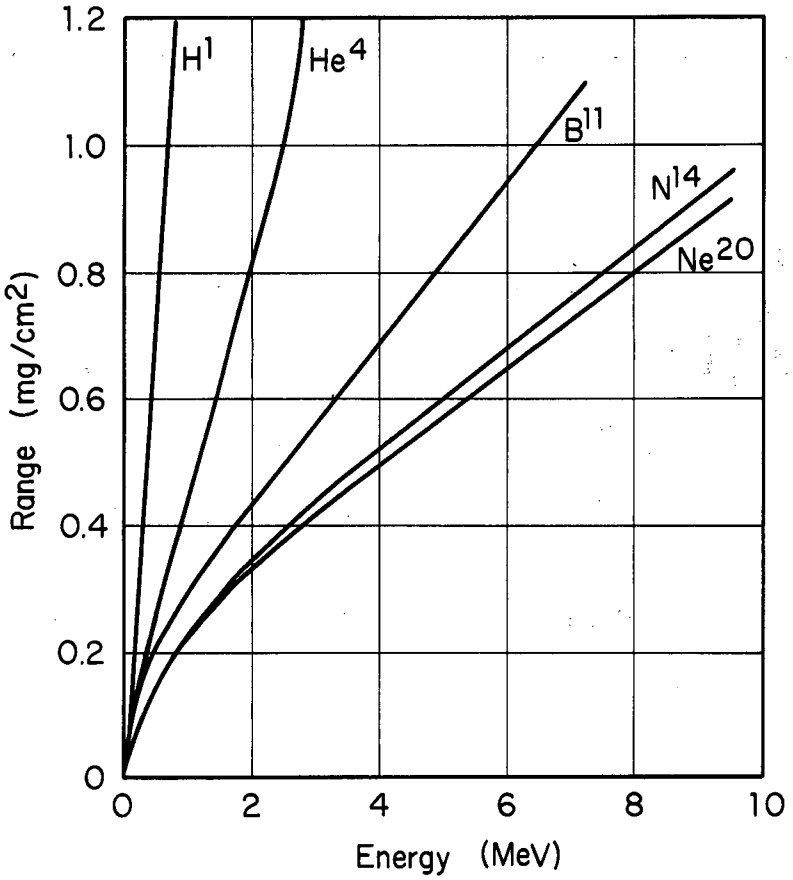


Fig. 7. Average ion charge vs ion velocity.
(From Gluckstern, 1954.)
——— modified theory in argon
experiment in argon
- - - - - experiment in nickel and Formvar foils
● experiment in organic film
(b) neon ions
(c) nitrogen ions



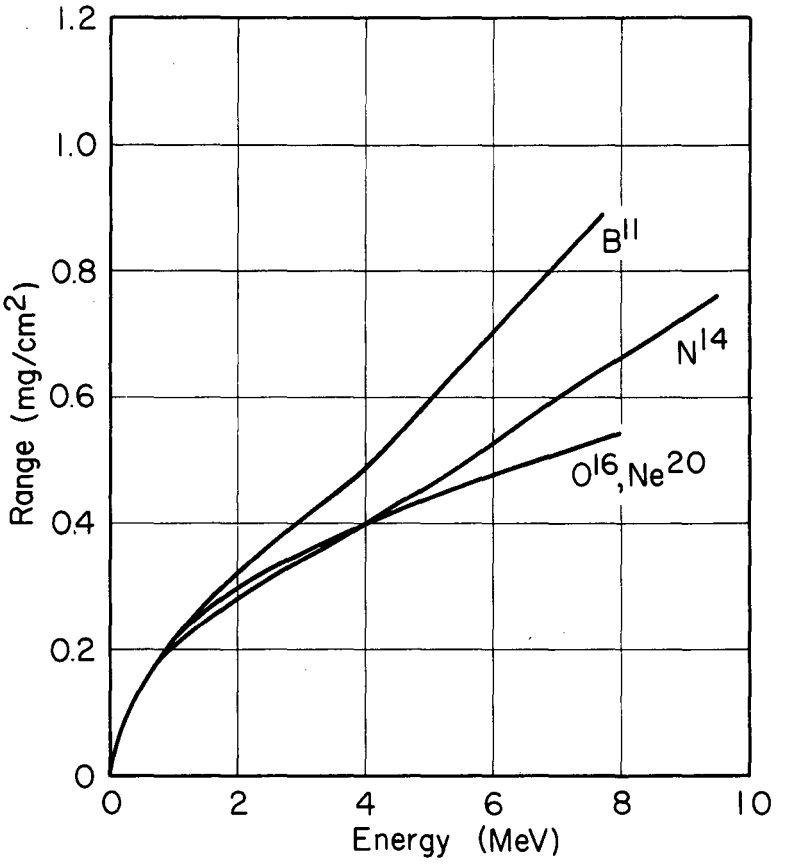
MU-29281

Fig. 8. Charge distribution vs stripper thickness for 8.7-MeV oxygen ions. (From Gluckstern, 1954.)
——— predictions of least-squares fit to data
experimental points for ionic charges +3, +4, +5, +6.



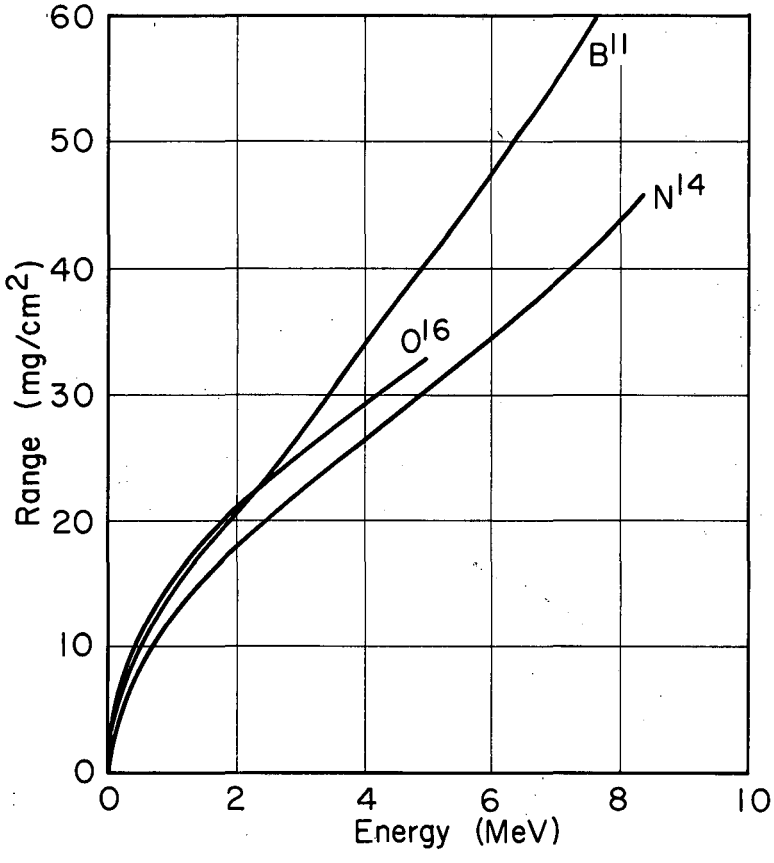
MU-29282

Fig. 9. Ranges of ions in air at 760 mm, 20° C ($\rho = 1.20$ mg/cm^3). [Redrawn from Teplova (1958).]



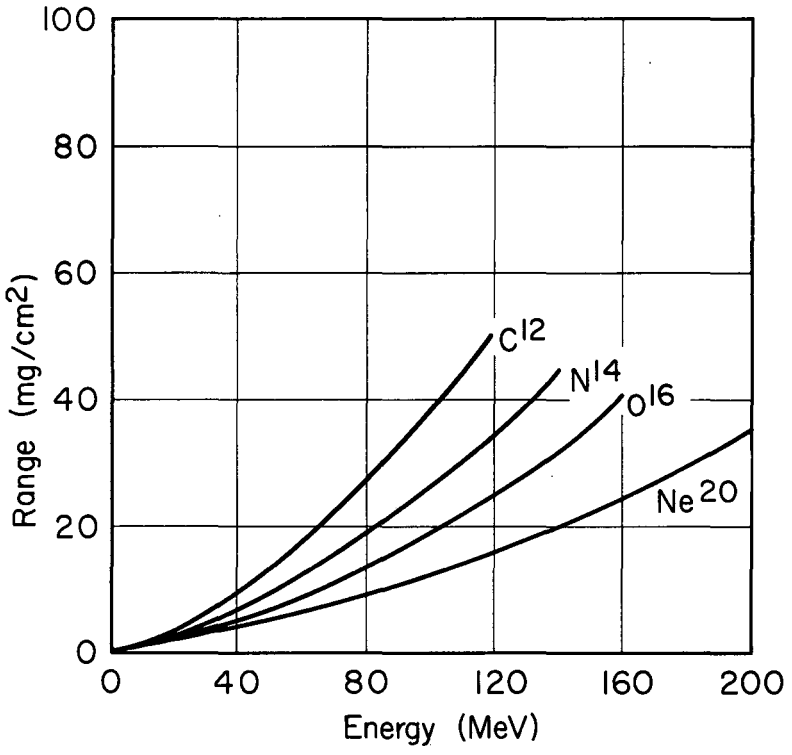
MU-29283

Fig. 10. Ranges of ions in argon at 760 mm, 20° C ($\rho = 1.66$ mg/cm^3). [Redrawn from Teplova (1958).]



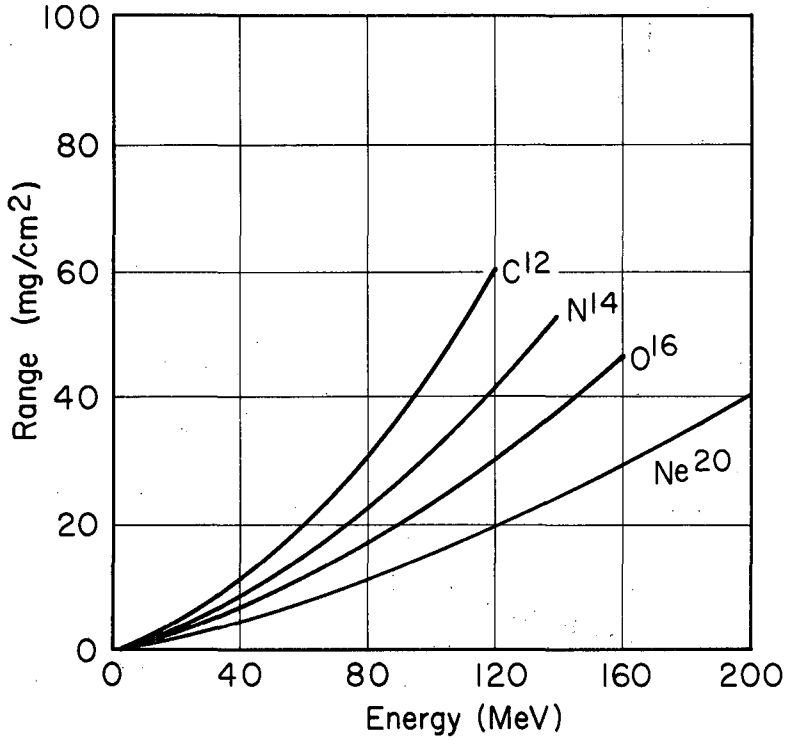
MU-29284

Fig. 11. Ranges of ions in hydrogen at 760 mm, 20° C ($\rho = 0.08$ mg/cm^3). [Redrawn from Teplova (1958).]



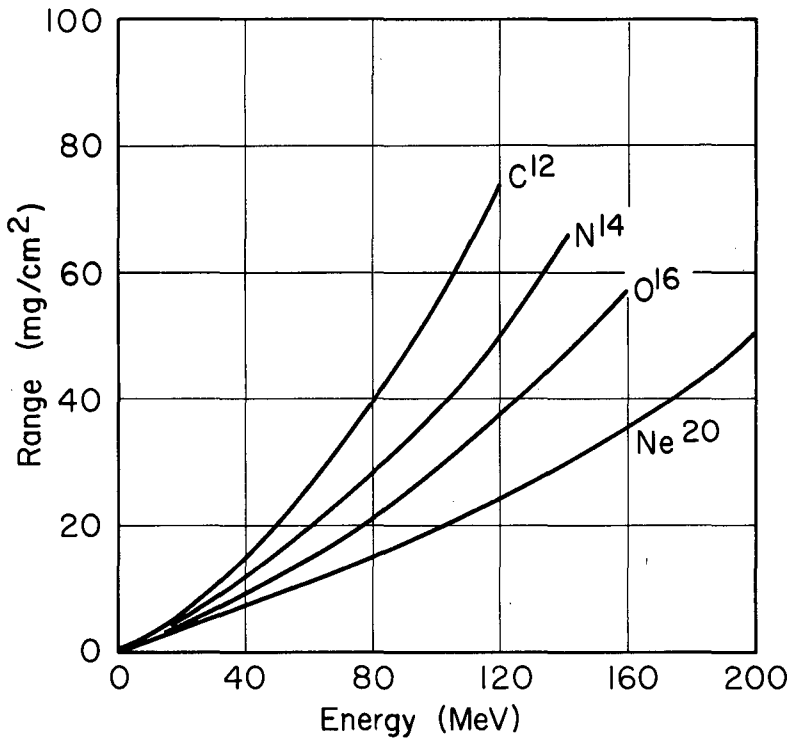
MU-29285

Fig. 12. Ranges of ions in beryllium. [Redrawn from Hubbard (1960).]



MU-29286

Fig. 13. Ranges of ions in aluminum. [Redrawn from Hubbard (1960).]



MU-29287

Fig. 14. Ranges of ions in nickel. [Redrawn from Hubbard (1960).]

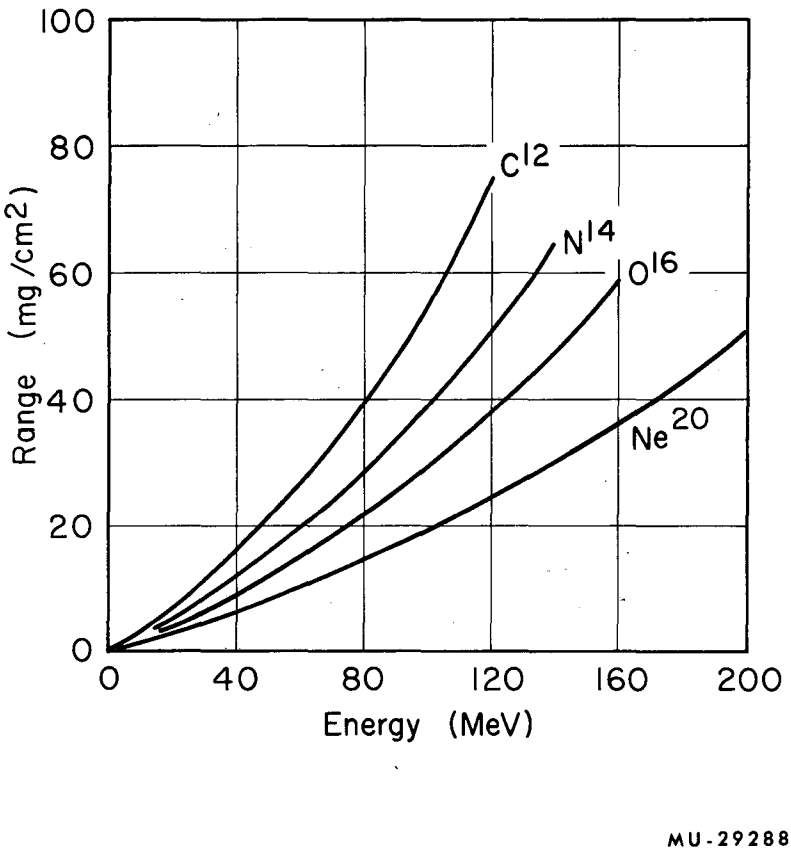
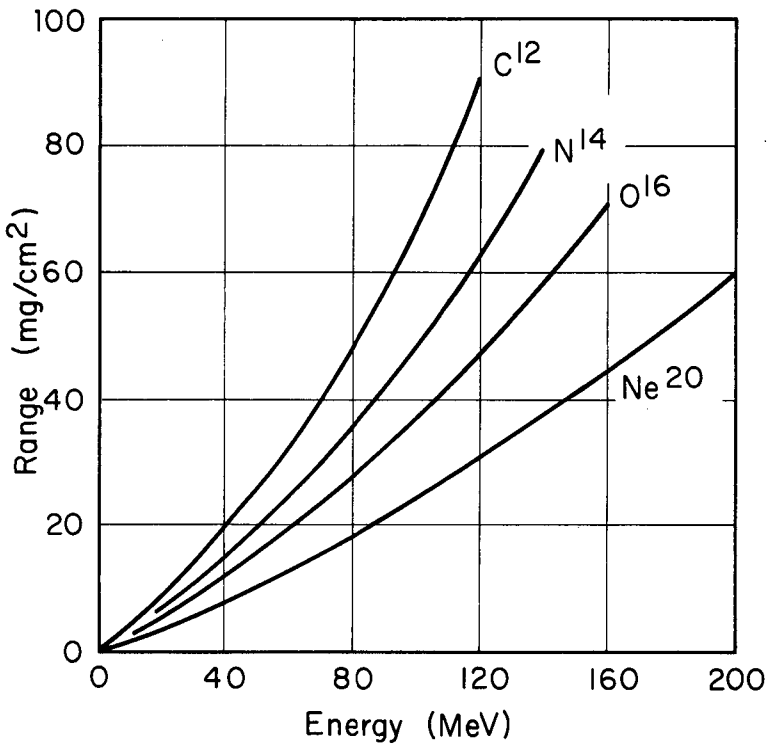


Fig. 15. Ranges of ions in copper. [Redrawn from Hubbard (1960).]



MU-29289

Fig. 16. Ranges of ions in silver. [Redrawn from Hubbard (1960).]

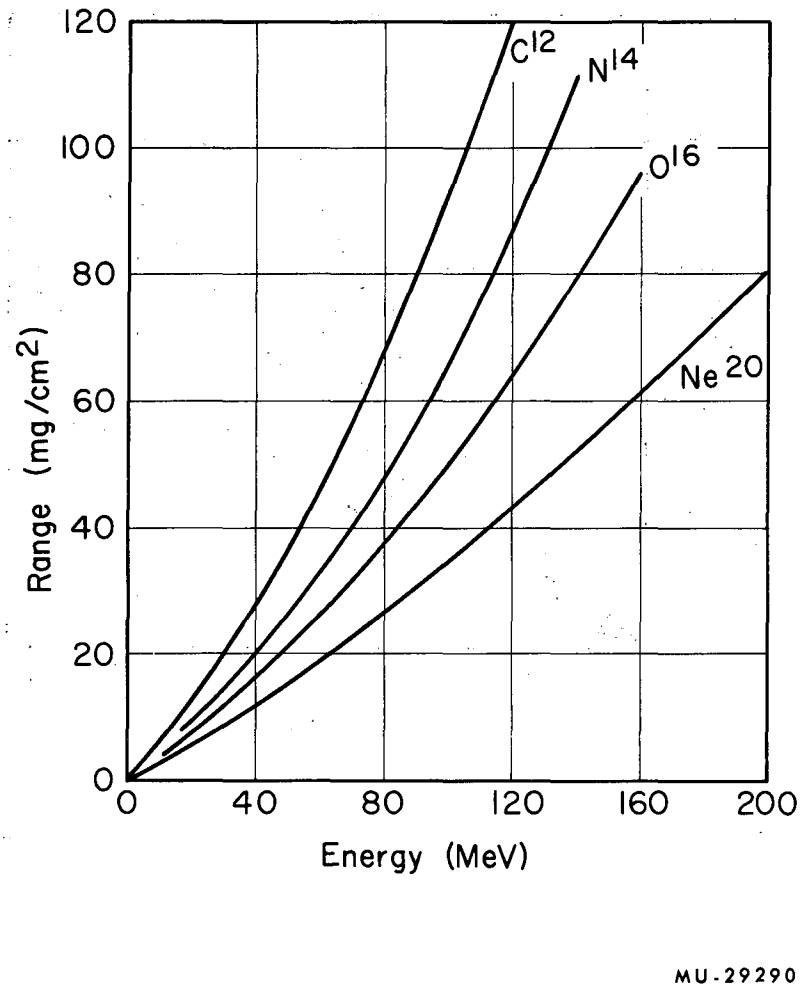


Fig. 17. Ranges of ions in gold. [Redrawn from Hubbard (1960).]

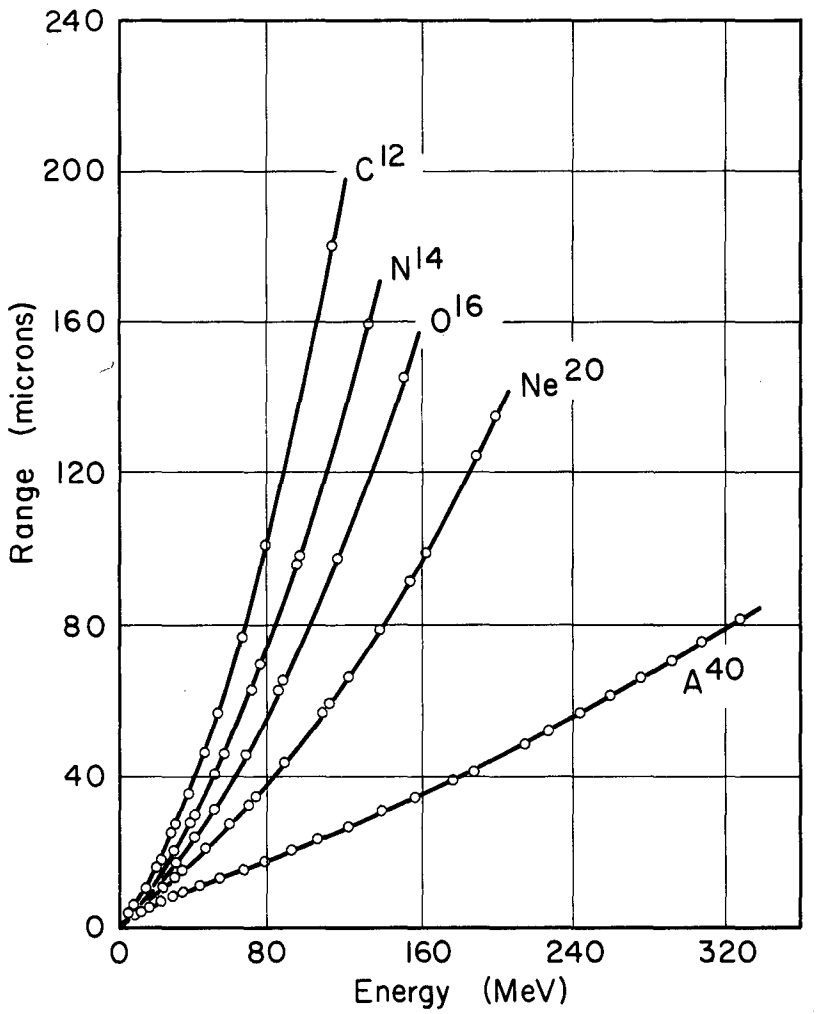


Fig. 18. Range-energy relations for C, N, O, Ne, and A ions in Ilford emulsion (3.815 g/cm^3). The curves through the experimental points are the least-squares polynomials fitted to the data. [From Heckman (1959).]

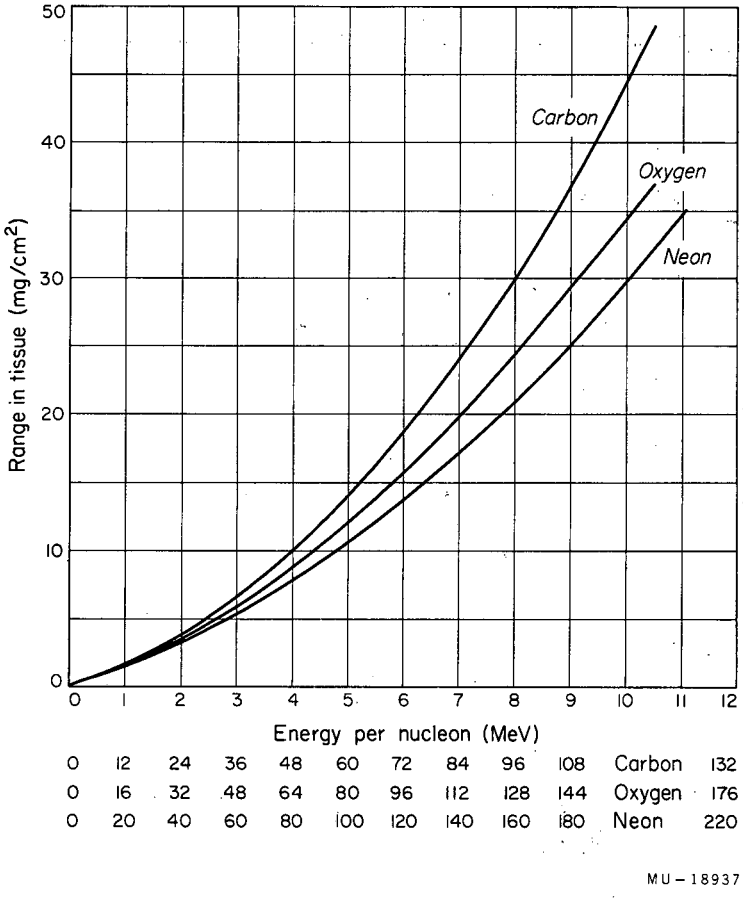
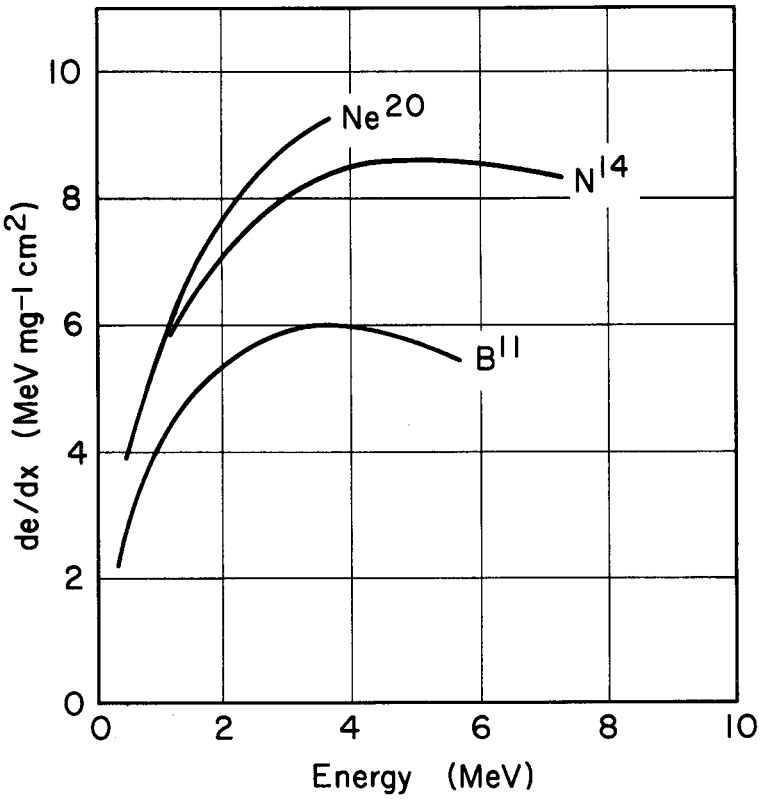
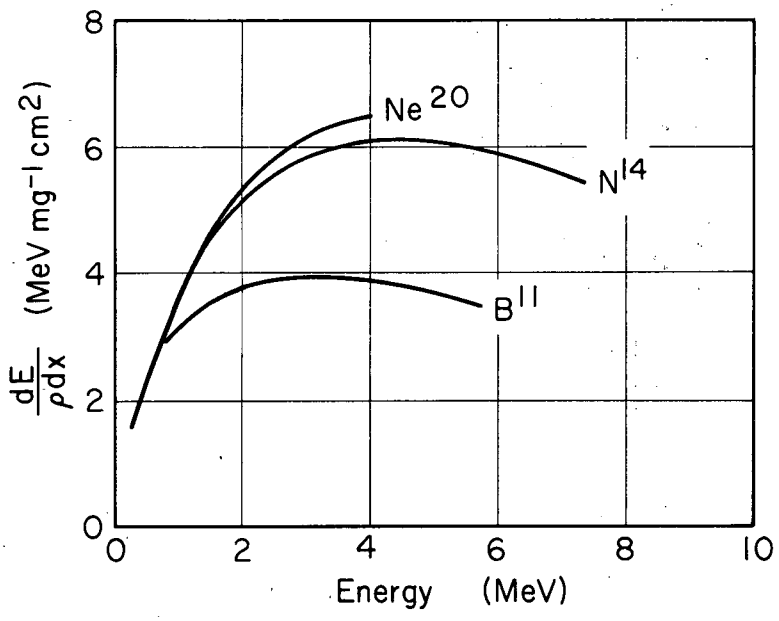


Fig. 19. Range-energy curves of C^{12}, O^{16}, and Ne^{20} in tissue.



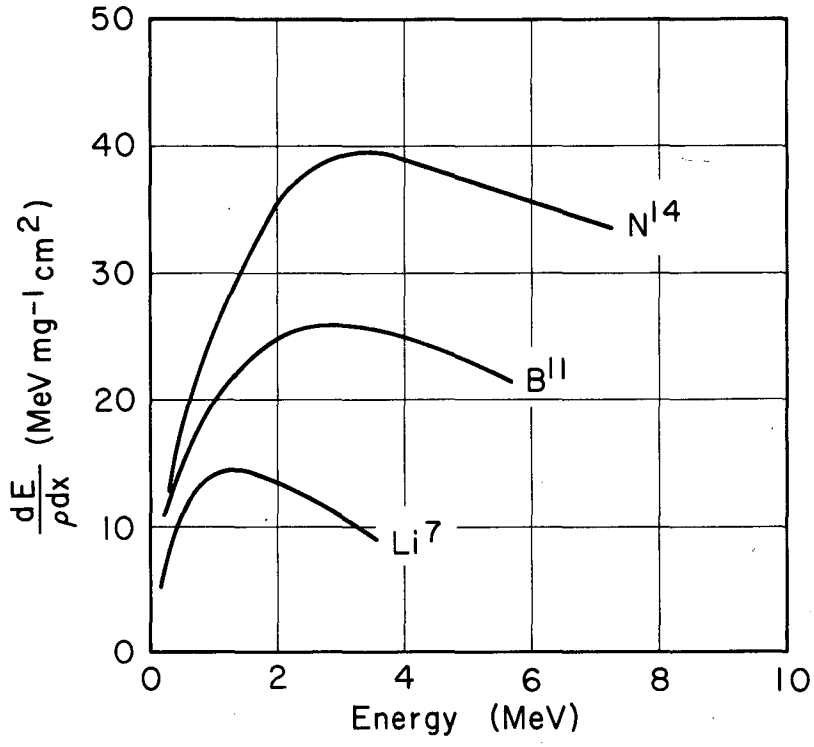
MU-29292

Fig. 20. $dE/\rho dx$ for ions in air at 760 mm, 20° C (ρ = 1.20 mg/cm^3). [Redrawn from Teplova (1958).]



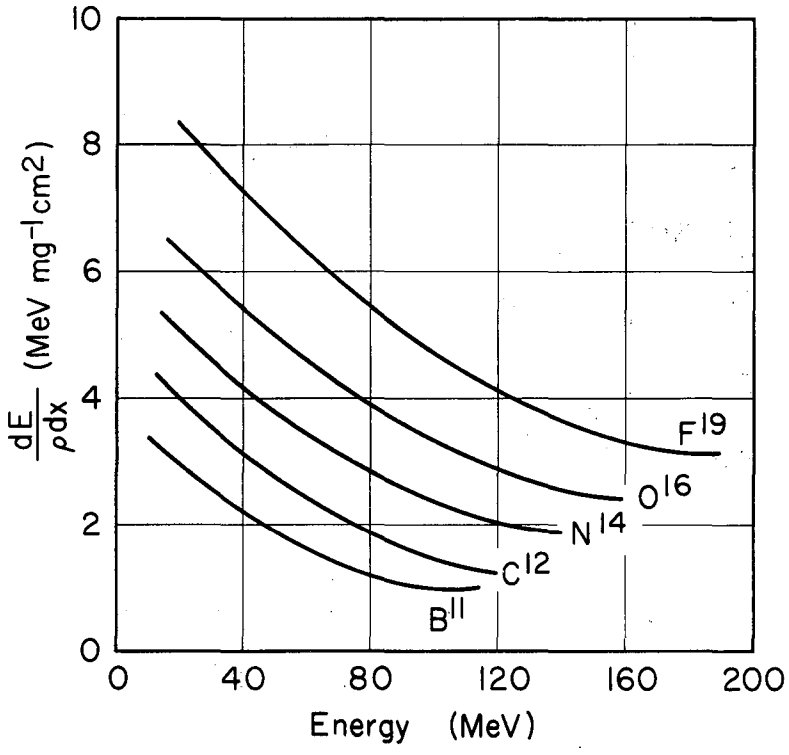
MU-29293

Fig. 21. dE/ρdx for ions in argon at 760 mm, 20° C (ρ = 1.66 mg/cm^3). [Redrawn from Teplova (1958).]



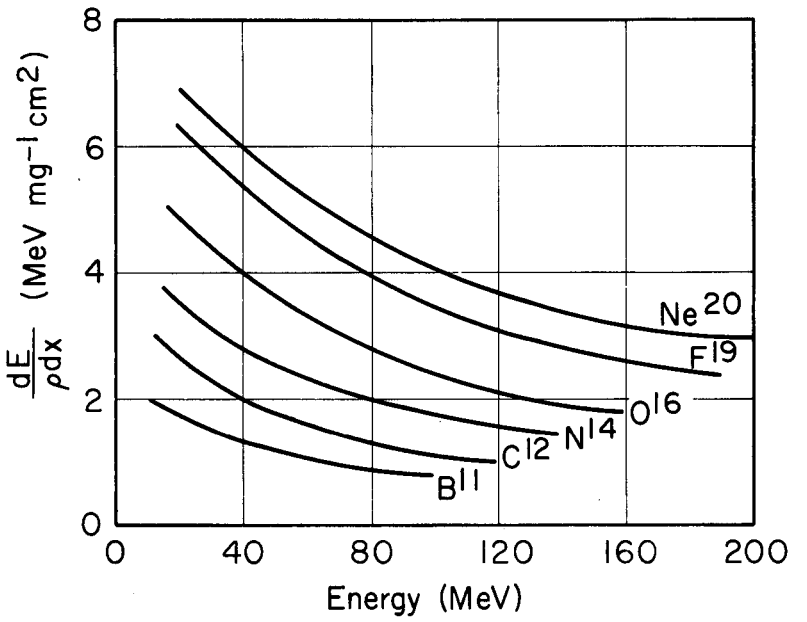
MU-29294

Fig. 22. $dE/\rho dx$ for ions in hydrogen at 760 mm, 20° C (ρ = 0.08 mg/cm^3). [Redrawn from Teplova (1958).]



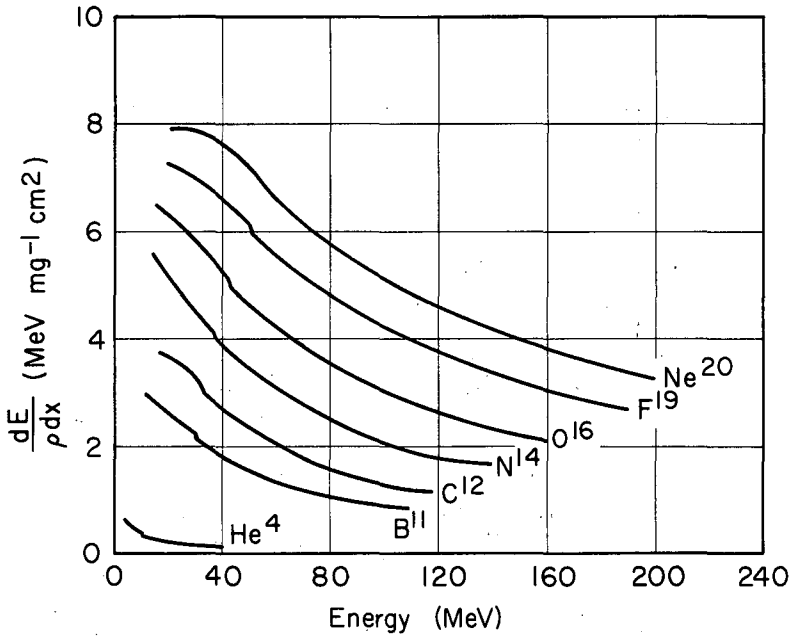
MU-29295

Fig. 23. dE/ρdx for ions in hydrogen at 760 mm, 20° C. (ρ = 0.08 mg/cm^3). [Redrawn from Roll and Steigert (1959).]



MU-29296

Fig. 24. dE/ρdx for ions in nickel. [Redrawn from Roll and Steigert (1959).]



MU-29297

Fig. 25. dE/ρdx for ions in aluminum. [Redrawn from Northcliffe (1959).]

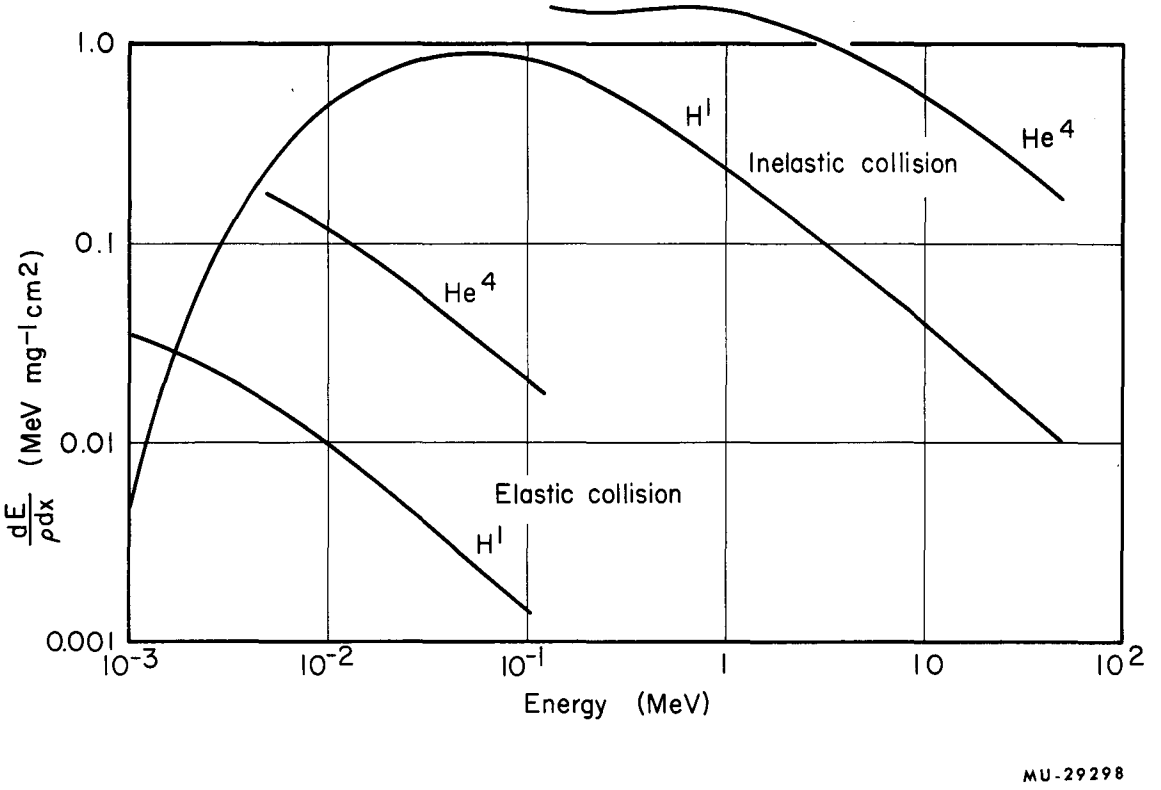


Fig. 26. $dE/\rho dx$ for H^1 and He^4 ions in tissue.
[Redrawn from Neufeld and Snyder (1960).]

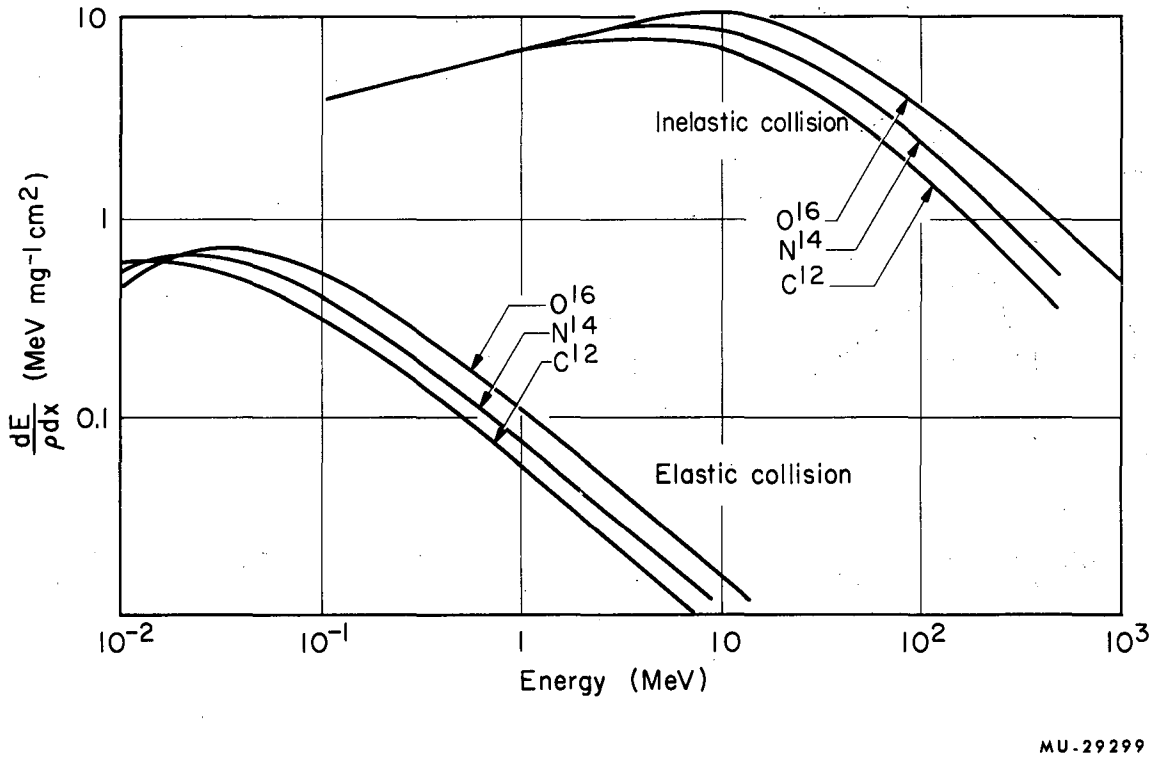


Fig. 27. dE/ρdx for ions in tissue. [Redrawn from Neufeld and Snyder (1960).]

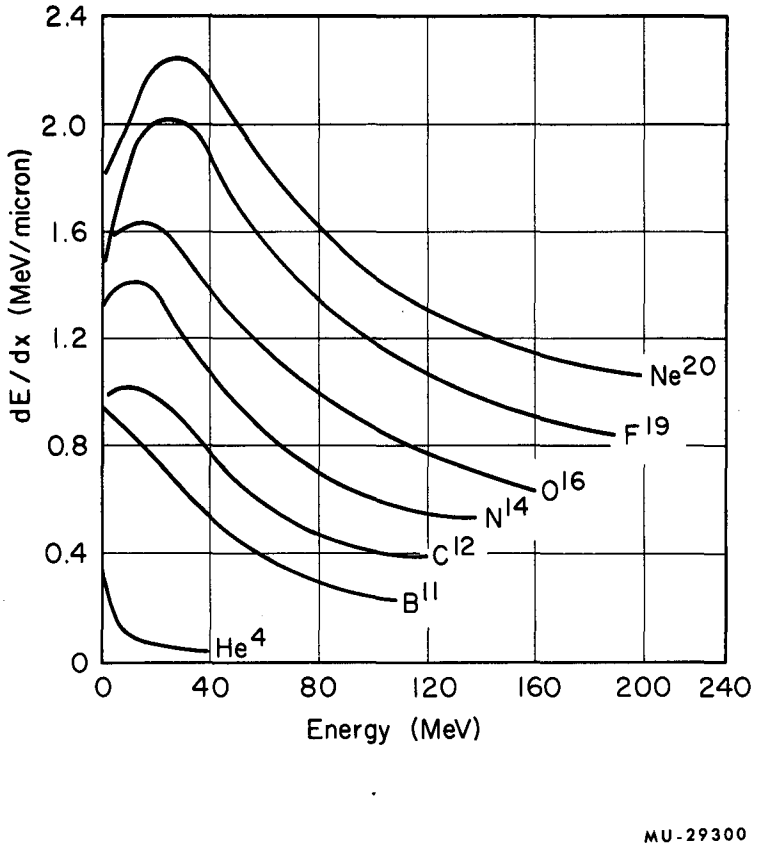
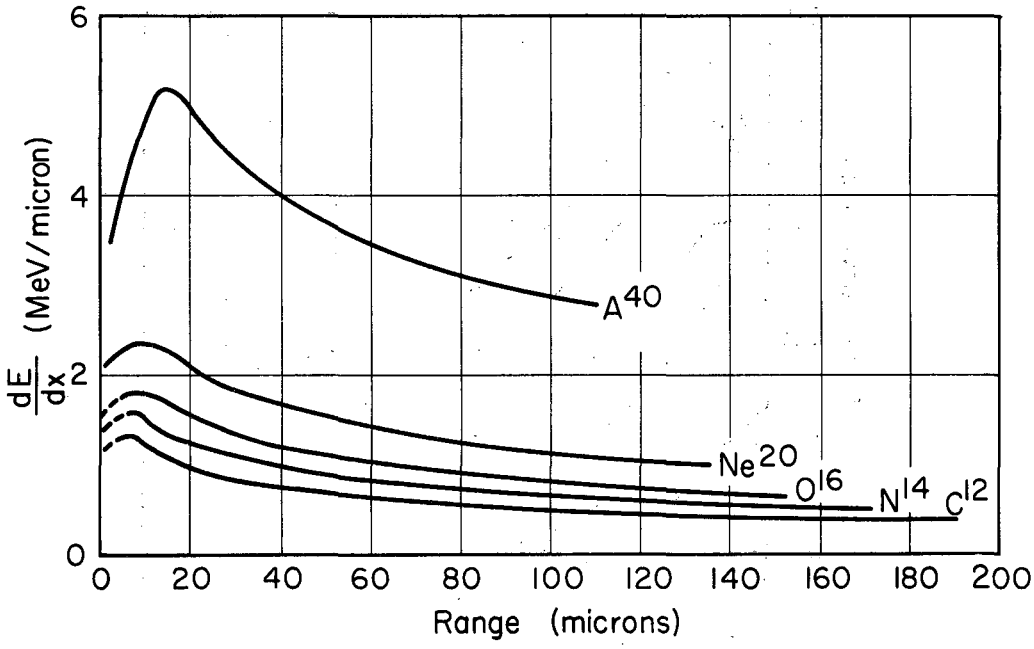
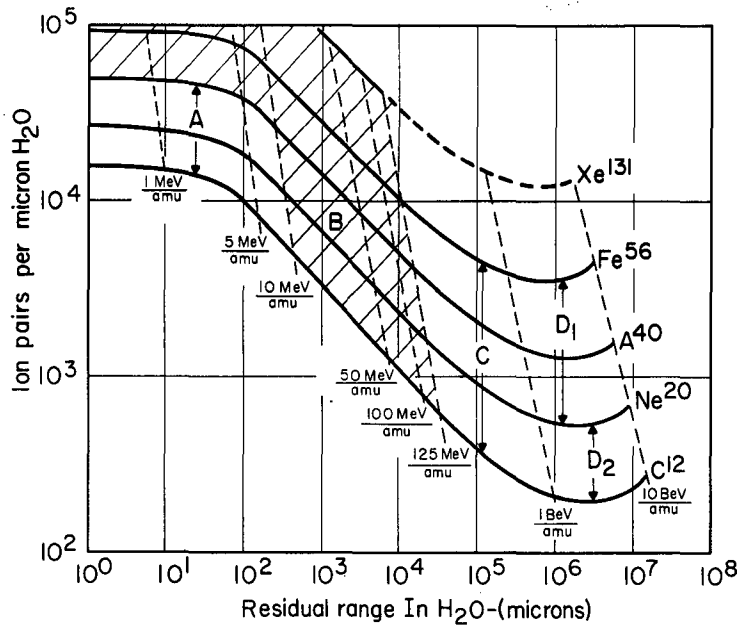


Fig. 28. dE/dx for ions in emulsion. [Redrawn from Roll and Steigert (1959).]



MU-29301

Fig. 29. dE/dx in emulsion as a function of residual range. The dashed parts of the curves show extrapolations to shorter ranges than were actually measured. [From Heckman (1959).]



MU-29302

Fig. 30. Specific ionization of heavy ions as a function of residual range in water. (Adapted from Simons, 1960.)

Regions

A: Hilac operating conditions (1 to 40 amu; up to 10 MeV/amu). Tracks have densely ionizing cores and limited radial δ rays, ending by thin-down tracks.

B: Additional region included by projected future accelerators (1 to 131 amu; to about 125 MeV/amu).

C: Region from 125 MeV/amu, at sunspot minima, to 1 BeV/amu at sunspot maxima. Minimum energy of particles that can penetrate to the top of the atmosphere at middle latitudes varies within this region; tracks have densely ionizing cores and extensive radial δ-ray patterns, and may have either thin-down or collision endings. The smaller particles in this region have somewhat less densely ionized track cores than the heavier particles.

D_1: 1 to 10 BeV/amu; 20 to 56 amu. Tracks have densely ionizing cores and extensive radial δ-ray patterns, and end by collisions.

D_2: 1 to 10 BeV/amu; 12 to 20 amu. Tracks have extensive radial δ rays and less densely ionizing cores, and end by collisions.

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