Title
RANGE-ENERGY RELATION FOR HEAVY IONS IK METALS



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# Radiation Laboratory

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## ABSTRACT

The range-energy relations for C, N, O, Ne, and A ions in Be, Al, Ni, Cu, Ag, and Au have been calculated from the experimental range-energy relation for these ions in emulsion. The calculated curves are compared with experiment in the cases for which experimental data are available.

# RANGE-ENERGY RELATION FOR HEAVY IONS IN METALS

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## Introduction

Very few measurements have been made of the ranges of heavy ions in metals other than aluminum. To provide experimenters with a set of range-energy curves until more measurements are made, the experimental range-energy relations for heavy ions in emulsions have been used to calculate the ranges in several metals frequently used by experimenters.

## Method of Calculation

The range of a heavy ion in a metal is related to the range of an $\alpha$ particle of the same velocity by the equation

$$R_{h,m} = \frac{4 M_h}{M_\alpha Z_h^2} R_{\alpha,m} + R_{ext,m} , \qquad (1)$$

where

$R_{h,m}$ = range of the heavy ion in a metal,

$R_{\alpha,m}$ = range of an $\alpha$ particle in the metal,

$M_h$ = mass of the heavy ion,

$Z_h$ = nuclear charge of the heavy ion,

$R_{ext,m}$ = a correction that must be added to the first term in Eq. (1) to account for the increase in range caused primarily by capture and loss of electrons by the ion near the end of its range.

Similarly the range of the heavy ion in nuclear emulsion is related to the range of an $\alpha$ particle in emulsion by

$$R_{h,em} = \frac{4 M_h}{M_\alpha Z_h^2} R_{\alpha,em} + R_{ext,em} , \qquad (2)$$

where the subscript em refers to emulsion.

Combining Eqs. (1) and (2) gives

$$R_{h,m} = \frac{R_{\alpha,m}}{R_{\alpha,em}} R_{h,em} \frac{1 - \dfrac{R_{ext,em}}{R_{h,em}}}{1 - \dfrac{R_{ext,m}}{R_{h,m}}}$$

$$R_{h,m} \simeq \frac{R_{\alpha,m}}{R_{\alpha,em}} R_{h,em} (1 - \Delta), \quad (3)$$

where

$$\Delta = \frac{R_{ext,em}}{R_{h,em}} - \frac{R_{ext,m}}{R_{h,m}} .$$

Since the average charge of an ion with a given velocity is not a sensitive function of the material it is going through, $\Delta \ll 1$ should be a good approximation.

Equation (3) then simplifies to

$$R_{h,m} = \frac{R_{\alpha,m}}{R_{\alpha,em}} R_{h,em} . \quad (4)$$

This expression has been used to calculate the ranges of C, N, O, Ne, and A ions in Al, Ni, Cu, Ag, Au, and Pb. The data of Barkas, Heckman, et al. were used for the ranges of heavy ions in emulsion[1] and of $\alpha$ particles in emulsion.[2] The ranges used for $\alpha$ particles in metals were those of Whaling.[3] Whaling does not quote ranges of $\alpha$ particles in Be. The ranges of heavy ions in Be were calculated from the ranges of protons in Be by using an expression analogous to Eq. (4). The range-energy data used for protons in Be were those of Bichsel, Mozeley, and Aron,[4] and the ranges in emulsion were taken from Heckman et al. and Barkas et al.[2]

## Results

The range-energy data calculated from Eq. (4) are given in Tables I through VI. The calculated curves for Be, Al, Cu, Ag, and Au are plotted in Figs. 1 through 5. In Figs. 6 through 17 the calculated curves are compared with experiment for those cases for which experimental data are available. The data of Walton and Hubbard, Sikkeland, and Gilmore are from stopping-power experiments done with the heavy-ion accelerator at Berkeley. The stopping-power experiments can be used only to check the shape of the range curves in the high-energy region. The point where the experimental data have been normalized to the calculated curves is indicated by a circle. The data for stopping in Ni from the Yale experiments of Roll and Steigert are treated in the same way. Burcham,[5] Northcliffe,[6] and Zucker et al.[7] also measured stopping power, but their measurements extended to low enough energy that they can be extrapolated to zero to get an absolute value for the range. The data of Oganesian were obtained from a paper by Flerov.[8] No description of the experiments was given.

Table I

Calculated ranges of C ions

| Energy (Mev) | Range (mg/cm$^2$) Al | Ni | Cu | Ag | Au | Pb |
|---|---|---|---|---|---|---|
| 12.0 | 3.1 | 4.6 | 4.3 | 5.6 | 7.6 | 8.2 |
| 24.0 | 6.2 | 8.7 | 8.5 | 11.0 | 15.3 | 15.3 |
| 36.0 | 9.9 | 13.4 | 13.4 | 17.2 | 23.9 | 23.3 |
| 48.0 | 14.4 | 19.0 | 19.2 | 24.1 | 34.4 | 32.3 |
| 60.0 | 20.0 | 25.9 | 26.1 | 32.5 | 45.0 | 43.4 |
| 75.0 | 28.1 | 35.5 | 35.9 | 44.3 | 41.2 | 58.6 |
| 89.9 | 37.4 | 46.7 | 47.0 | 57.7 | 79.1 | 76.6 |
| 104.9 | 48.0 | 59.2 | 60.2 | 73.2 | 98.0 | 96.3 |
| 119.9 | 60.1 | 73.6 | 75.0 | 89.9 | 121.1 | 118.7 |

Table II

Calculated ranges of N ions

| Energy (Mev) | Range (mg/cm$^2$) Al | Ni | Cu | Ag | Au | Pb |
|---|---|---|---|---|---|---|
| 14.0 | 3.1 | 4.6 | 4.2 | 5.5 | 7.6 | 8.1 |
| 28.0 | 5.9 | 8.3 | 8.2 | 10.5 | 14.7 | 14.6 |
| 42.0 | 9.3 | 12.5 | 12.5 | 16.1 | 22.4 | 21.8 |
| 56.0 | 13.3 | 17.5 | 17.7 | 22.2 | 30.8 | 29.8 |
| 70.0 | 18.1 | 23.5 | 23.6 | 29.4 | 40.8 | 39.4 |
| 87.5 | 25.2 | 31.8 | 32.1 | 39.7 | 54.8 | 52.5 |
| 104.9 | 33.3 | 41.6 | 41.9 | 51.4 | 70.4 | 68.2 |
| 122.4 | 42.3 | 52.2 | 53.2 | 64.6 | 86.5 | 85.0 |
| 139.9 | 52.8 | 64.7 | 65.9 | 79.1 | 106.5 | 104.4 |

Table III

Calculated ranges of O ions

| Energy (Mev) | Range (mg/cm$^2$) Al | Ni | Cu | Ag | Au | Pb |
|---|---|---|---|---|---|---|
| 16.0 | 3.1 | 4.5 | 4.2 | 5.5 | 7.5 | 8.0 |
| 32.0 | 5.6 | 7.9 | 7.8 | 10.0 | 14.0 | 14.0 |
| 48.0 | 8.7 | 11.8 | 11.8 | 15.1 | 21.0 | 20.5 |
| 63.9 | 12.3 | 16.2 | 16.4 | 20.6 | 28.6 | 27.7 |
| 79.9 | 16.7 | 21.6 | 21.8 | 27.1 | 37.5 | 36.3 |
| 99.9 | 23.0 | 29.1 | 29.4 | 36.3 | 50.1 | 48.0 |
| 119.9 | 30.3 | 37.8 | 38.1 | 46.7 | 64.0 | 62.0 |
| 139.9 | 38.5 | 47.4 | 48.3 | 58.7 | 78.6 | 77.2 |
| 159.8 | 47.6 | 58.3 | 59.4 | 71.2 | 96.0 | 94.1 |

Table IV

Calculated range of Ne ions

| Energy (Mev) | Range (mg/cm$^2$) Al | Ni | Cu | Ag | Au | Pb |
|---|---|---|---|---|---|---|
| 20.0 | 3.0 | 4.4 | 4.0 | 5.3 | 7.2 | 7.8 |
| 40.0 | 5.3 | 7.5 | 7.4 | 9.5 | 13.2 | 13.2 |
| 59.9 | 8.0 | 10.9 | 10.9 | 14.0 | 19.4 | 18.9 |
| 79.9 | 11.2 | 14.8 | 14.9 | 18.8 | 26.0 | 25.2 |
| 99.9 | 15.0 | 19.4 | 19.5 | 24.3 | 33.7 | 32.5 |
| 124.9 | 20.3 | 25.7 | 26.0 | 32.1 | 44.2 | 42.4 |
| 149.9 | 26.4 | 33.0 | 33.2 | 40.8 | 55.9 | 54.1 |
| 174.8 | 33.1 | 40.8 | 41.5 | 50.5 | 67.6 | 66.4 |
| 199.8 | 40.6 | 49.8 | 50.7 | 60.8 | 82.0 | 80.3 |

Table V

Calculated ranges of A ions

| Energy (Mev) | Range (mg/cm$^2$) Al | Ni | Cu | Ag | Au | Pb |
|---|---|---|---|---|---|---|
| 39.9 | 3.3 | 4.9 | 4.5 | 6.0 | 8.1 | 8.7 |
| 79.9 | 5.4 | 7.6 | 7.4 | 9.6 | 13.4 | 13.4 |
| 119.8 | 7.6 | 10.3 | 10.3 | 13.3 | 18.5 | 18.0 |
| 159.7 | 10.3 | 13.5 | 13.6 | 17.2 | 23.8 | 23.0 |
| 199.7 | 13.2 | 17.1 | 17.2 | 21.4 | 29.8 | 28.6 |
| 249.6 | 17.4 | 22.0 | 22.2 | 27.4 | 37.8 | 36.2 |
| 299.5 | 21.9 | 27.3 | 27.5 | 33.8 | 46.3 | 44.6 |
| 349.4 | 26.8 | 33.1 | 33.7 | 40.9 | 54.8 | 53.9 |
| 399.4 | 32.3 | 39.5 | 40.3 | 48.3 | 65.1 | 63.8 |

Table VI

Calculated ranges of heavy ions in Be

| C Energy Mev | C Range mg/cm$^2$ | N Energy Mev | N Range mg/cm$^2$ | O Energy Mev | O Range mg/cm$^2$ | Ne Energy Mev | Ne Range mg/cm$^2$ | A Energy Mev | A Range mg/cm$^2$ |
|---|---|---|---|---|---|---|---|---|---|
| 11.9 | 1.9 | 13.9 | 1.9 | 15.9 | 1.9 | 19.8 | 1.8 | 39.7 | 2.1 |
| 23.8 | 4.6 | 27.8 | 4.3 | 31.7 | 4.2 | 39.7 | 3.9 | 79.4 | 4.0 |
| 35.7 | 7.8 | 41.6 | 7.2 | 47.6 | 6.8 | 59.5 | 6.3 | 119.0 | 6.0 |
| 47.6 | 11.7 | 55.5 | 10.7 | 63.5 | 10.1 | 79.4 | 9.1 | 158.7 | 8.4 |
| 59.5 | 16.1 | 69.4 | 14.6 | 79.4 | 13.7 | 99.2 | 12.4 | 198.4 | 11.0 |
| 71.4 | 21.6 | 83.3 | 19.4 | 95.2 | 18.2 | 119.0 | 16.1 | 238.1 | 13.9 |
| 83.3 | 28.1 | 97.2 | 24.9 | 111.1 | 22.8 | 138.9 | 19.9 | 277.8 | 16.9 |
| 95.2 | 35.3 | 111.0 | 31.0 | 127.0 | 27.9 | 158.7 | 24.4 | 317.4 | 20.3 |
| 107.1 | 42.8 | 124.9 | 37.2 | 142.8 | 33.7 | 178.6 | 29.2 | 356.9 | 23.9 |
| 119.0 | 50.9 | 139.0 | 45.0 | 158.7 | 40.2 | 198.4 | 34.8 | 396.5 | 27.7 |

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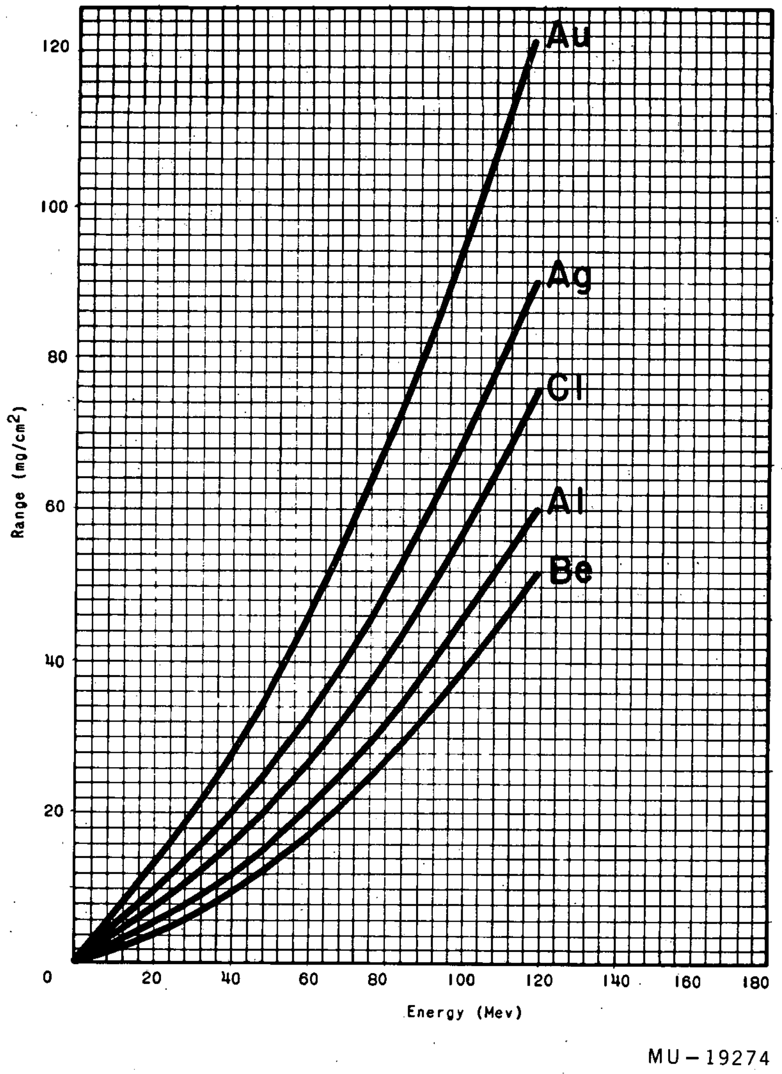


Fig. 1. Calculated range-energy relations for $C^{12}$ ions in Be, Al, Cu, Ag, and Au.

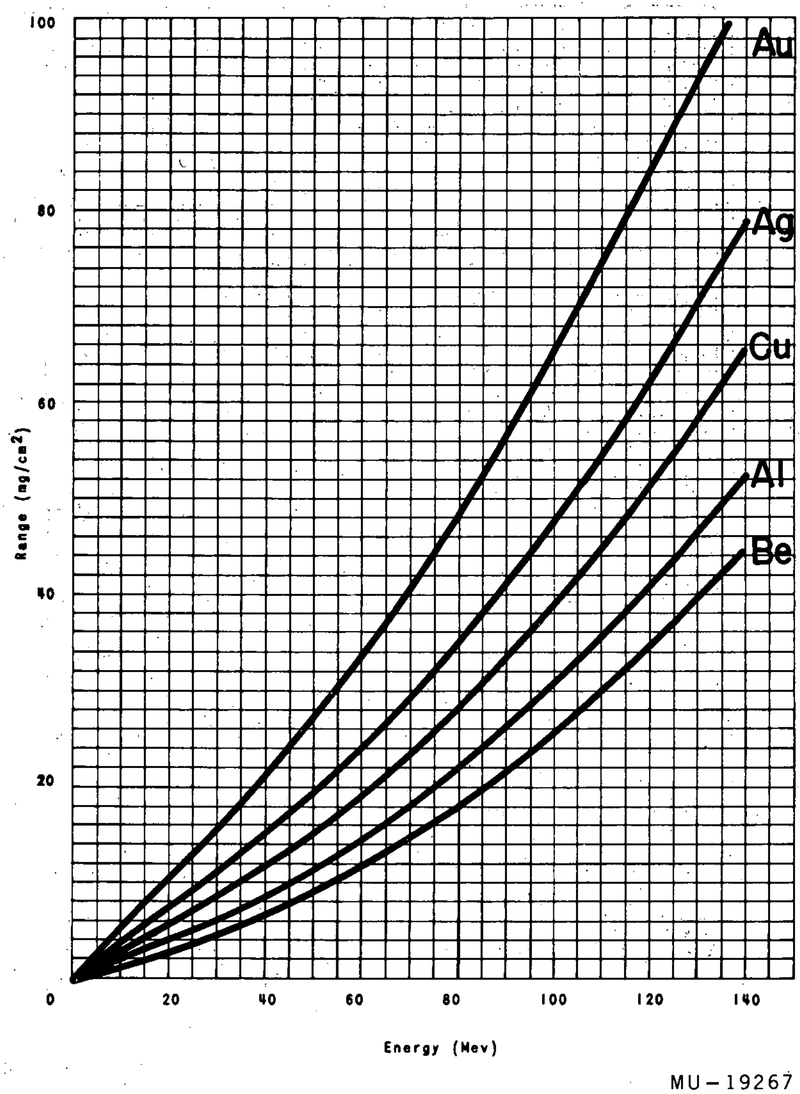


Fig. 2. Calculated range-energy relations for $N^{14}$ ions in Be, Al, Cu, Ag, and Au.

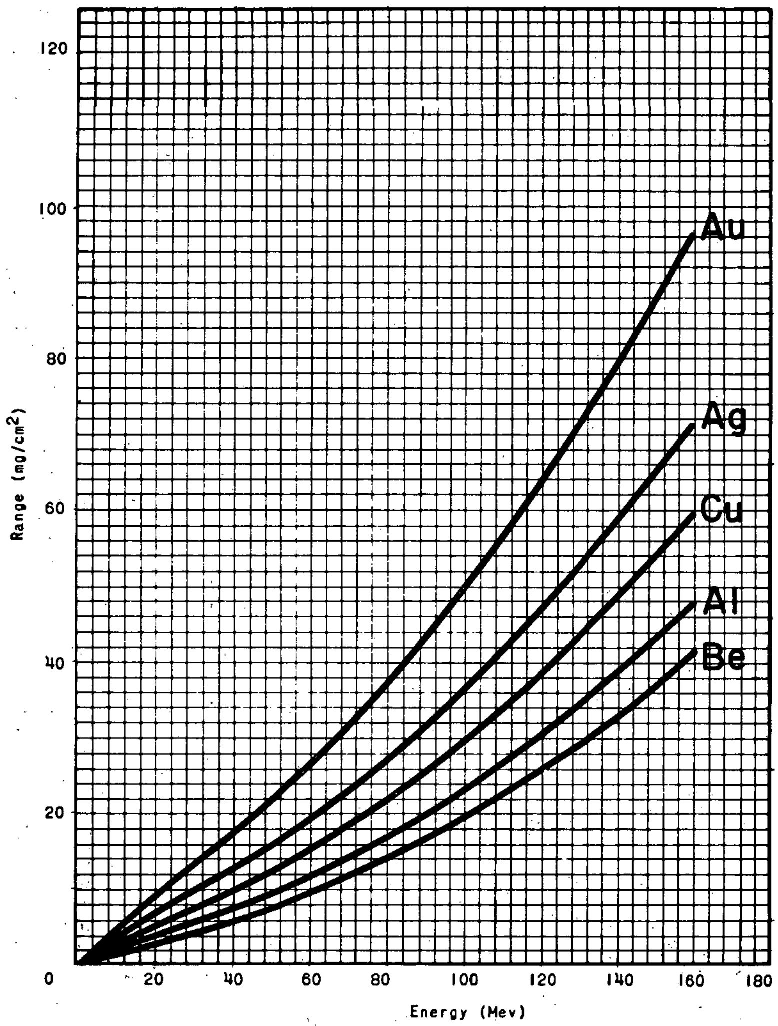


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Fig. 3. Calculated range-energy relations for $O^{16}$ ions in Be, Al, Cu, Ag, and Au.

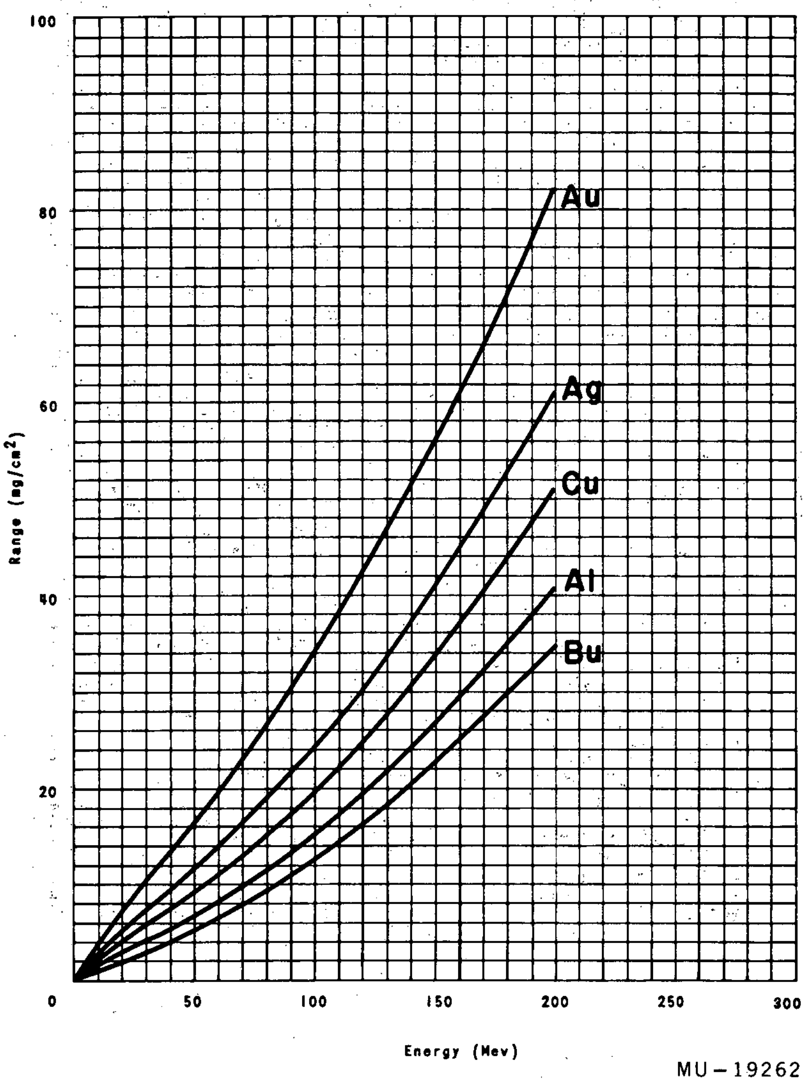


Fig. 4. Calculated range-energy relations for $Ne^{20}$ ions in Be, Al, Cu, Ag, and Au.

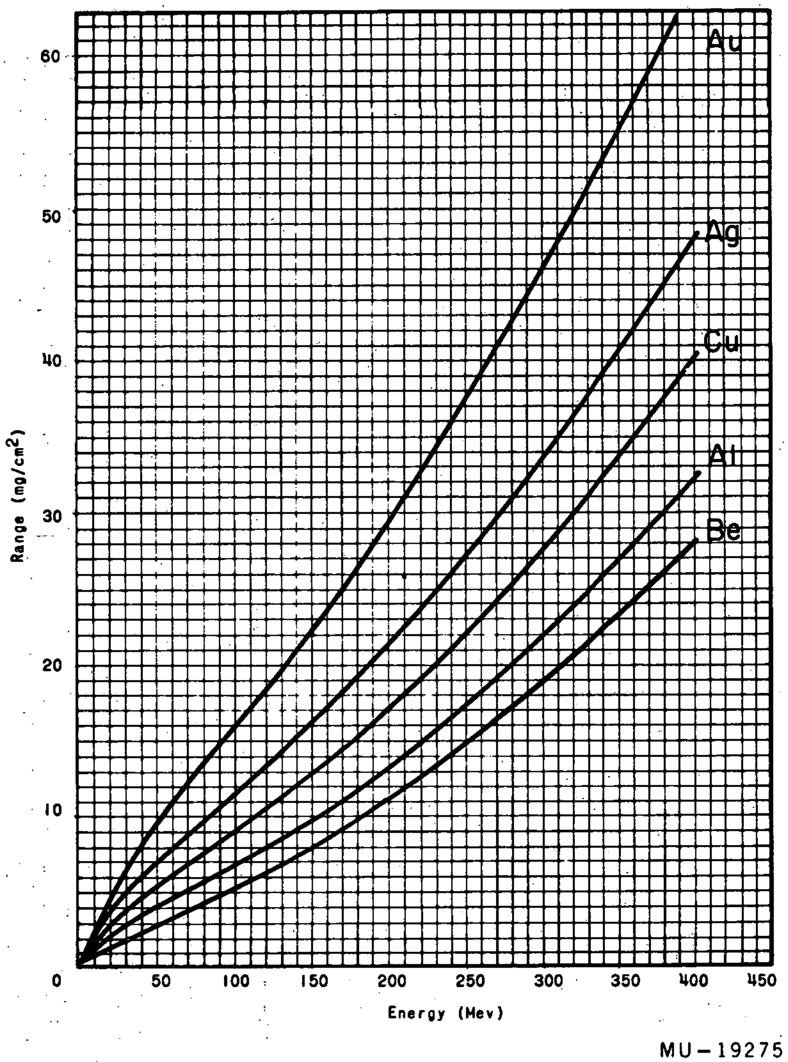


Fig. 5. Calculated range-energy relations for $A^{40}$ ions in Be, Al, Cu, Ag, and Au.

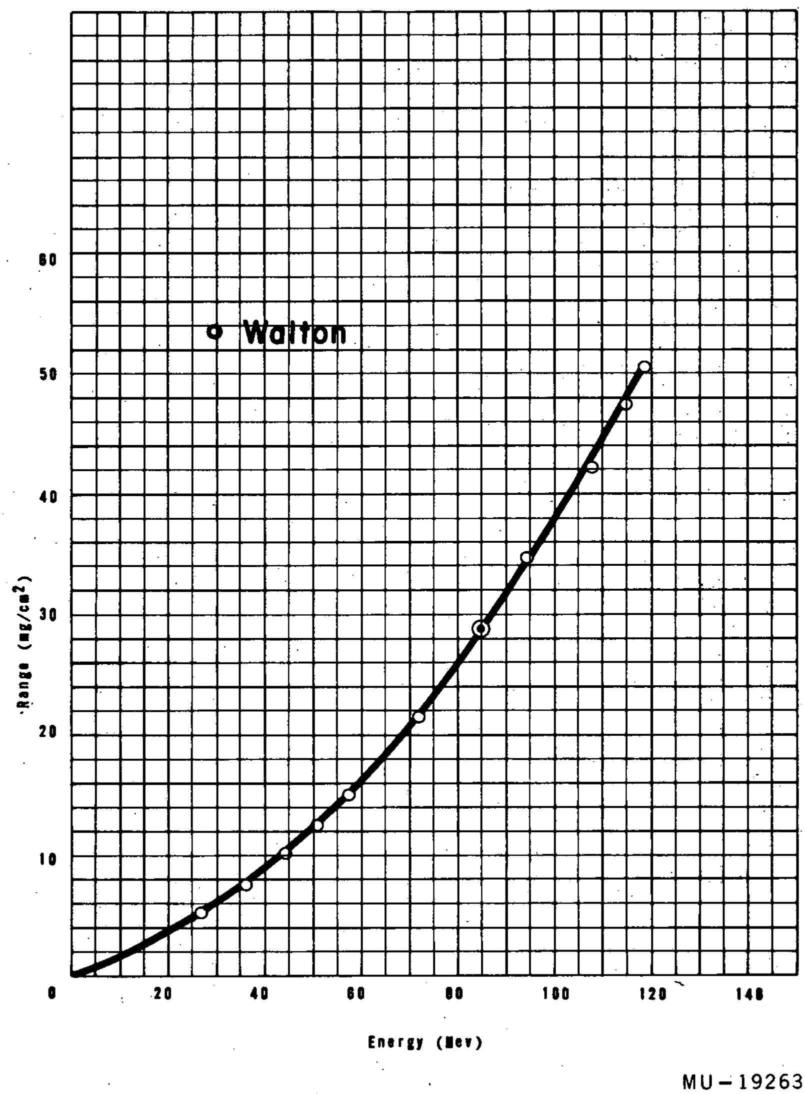


Fig. 6. Range-energy relation for $C^{12}$ ions in beryllium. Solid curve was calculated from emulsion data. Walton's energy-loss data were fitted to the calculated range curve at the point circled.

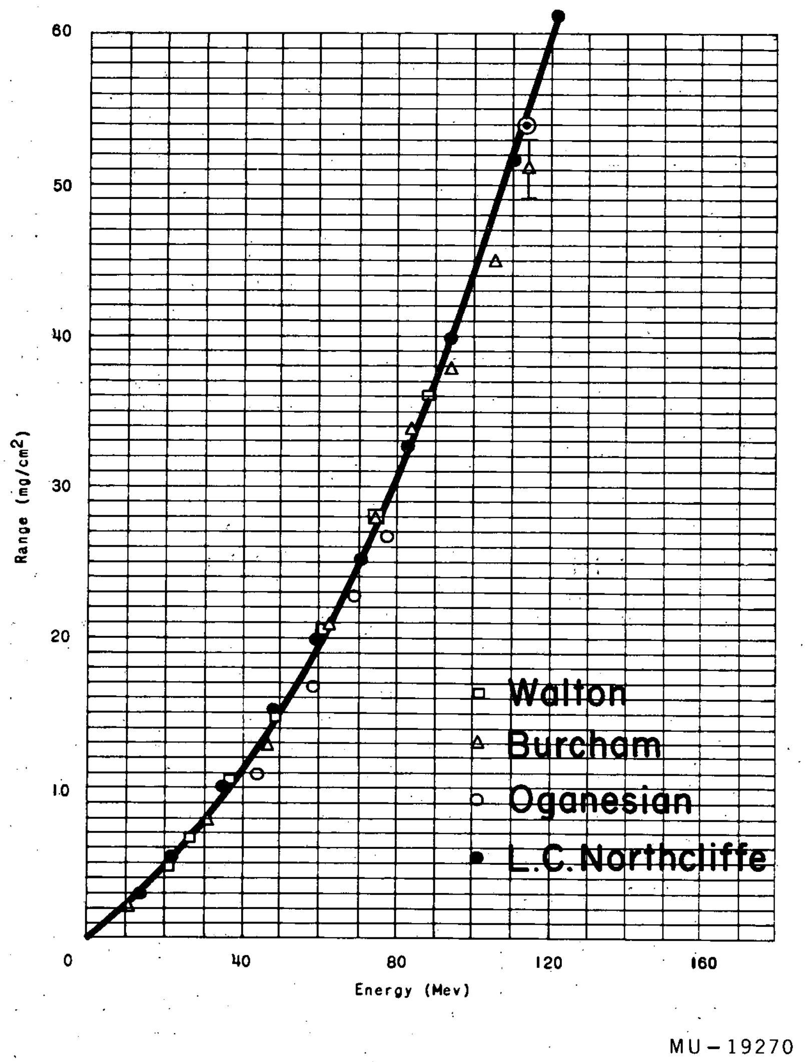


Fig. 7. Range-energy relation for $C^{12}$ ions in aluminum. The solid curve was calculated from Eq. (4). The energy-loss data of Walton were fitted to the calculated range curve at the point circled. The energy-loss data of Northcliffe and Burcham were converted to range data by extrapolating to zero.

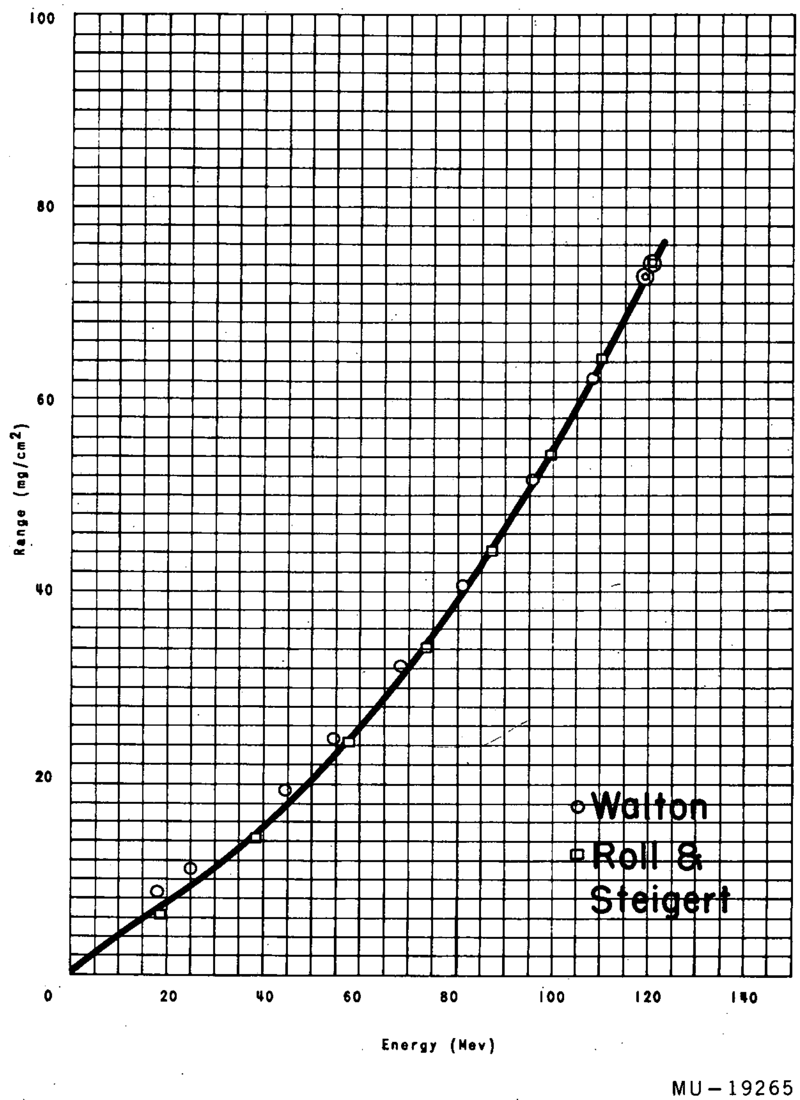


Fig. 8. Range-energy relation for $C^{12}$ ions in nickel. The solid curve was calculated from Eq. (4). Experimental energy-loss data were fitted to the calculated curve at the points circled.

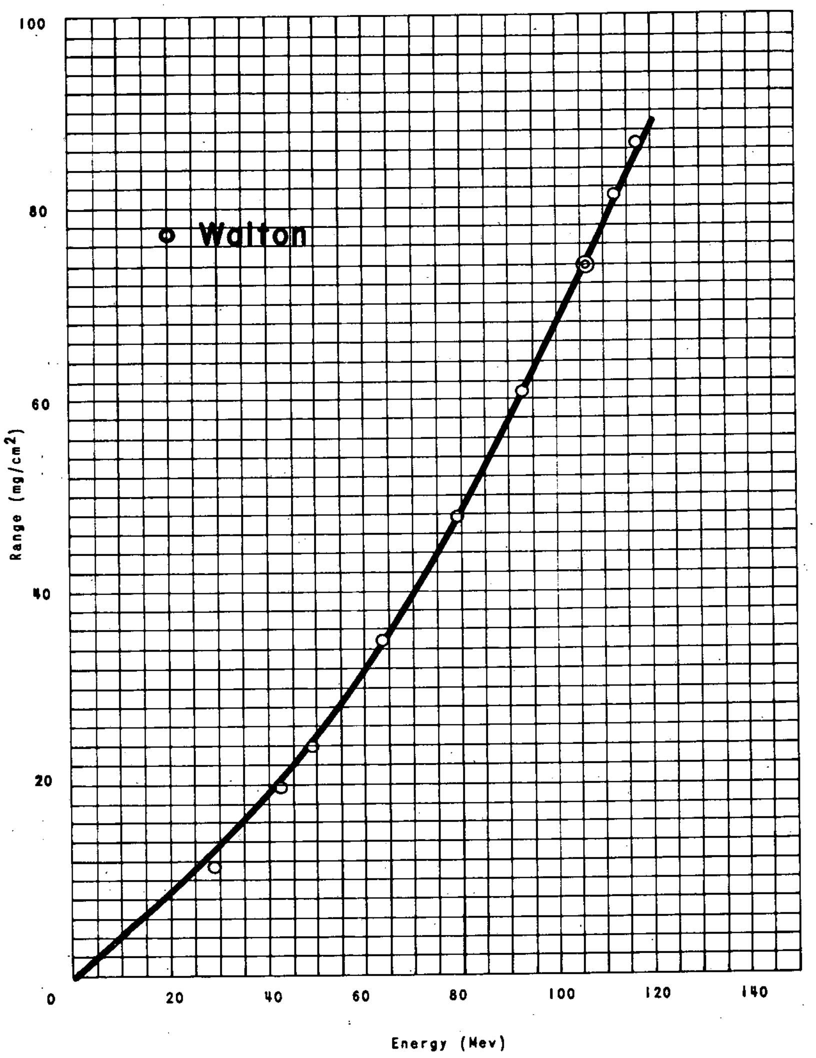


Fig. 9. Range-erergy relation for $C^{12}$ ions in silver. The solid curve was calculated from Eq. (4). Walton's energy-loss data were fitted to the calculated range curve at the point circled.

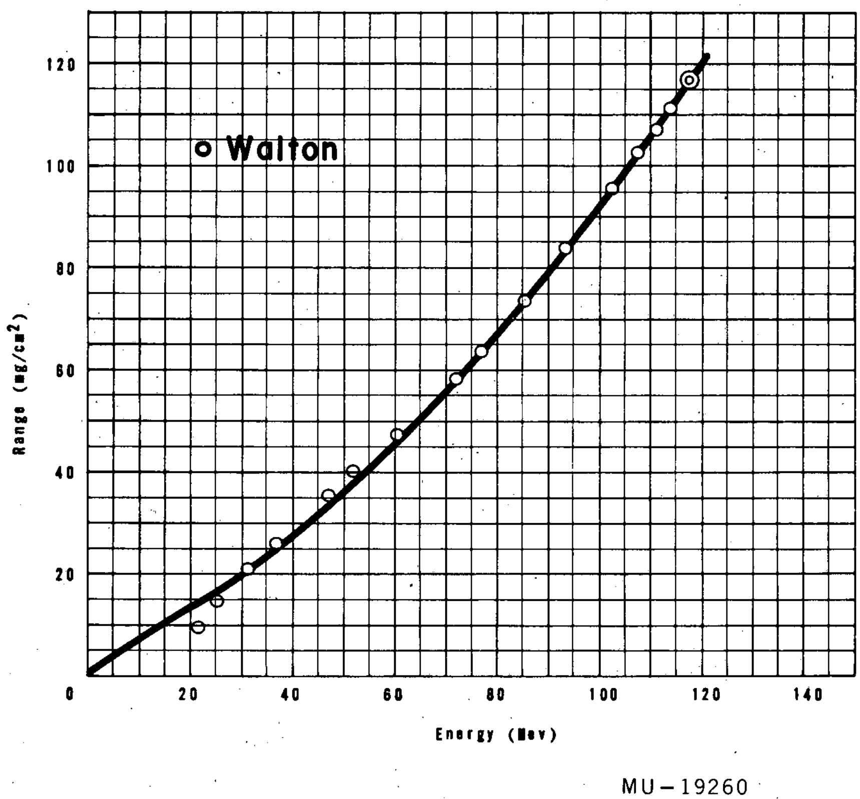


Fig. 10. Range-energy relation for $C^{12}$ ions in gold. The solid curve was calculated from Eq. (4). Walton's energy-loss data were fitted to the calculated range curve at the point circled.

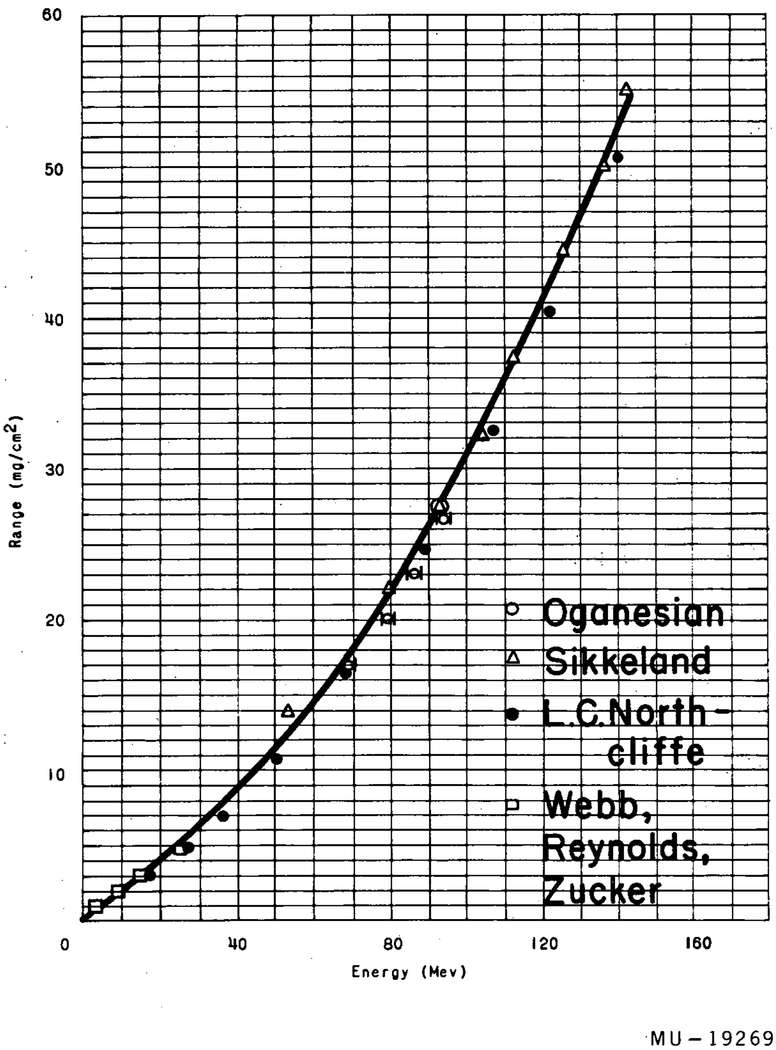


Fig. 11. Range-energy relation for $N^{14}$ ions in aluminum. The solid curve was calculated from Eq. (4). Sikkeland's energy-loss data were fitted to the calculated range curve at the point circled. The energy-loss data of Northcliffe and Zucker et al. was converted to range data by extrapolating to zero.

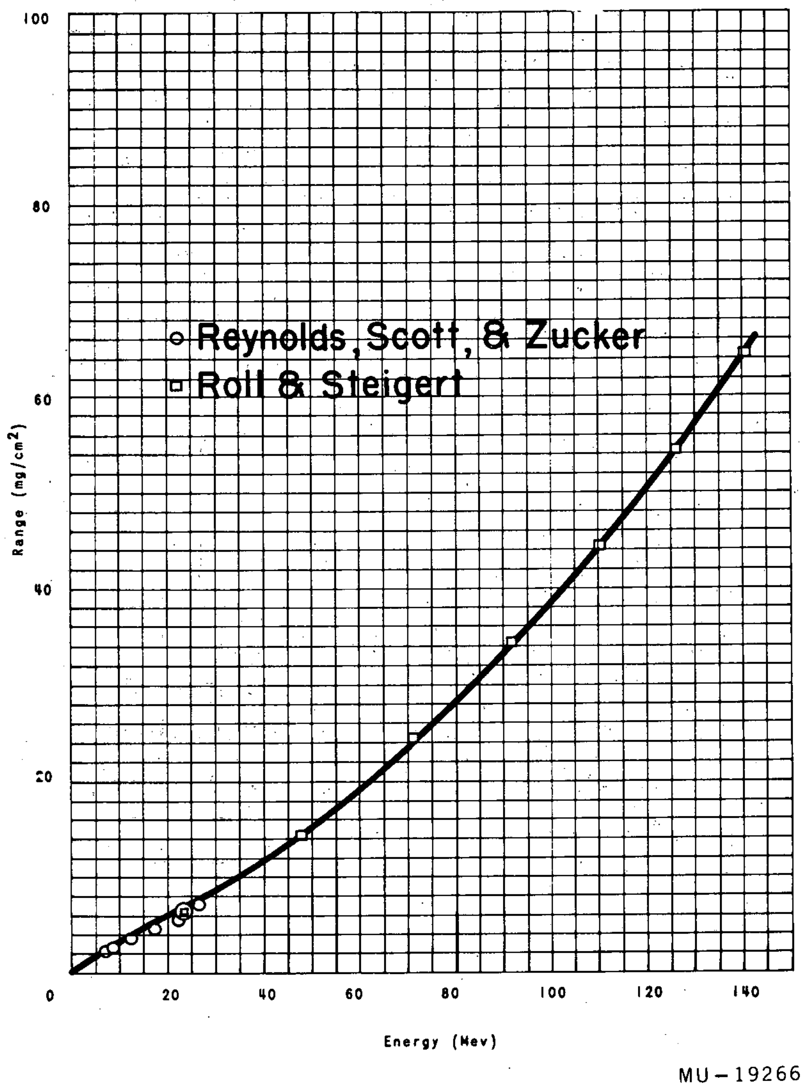


Fig. 12. Range-energy relation for $N^{14}$ ions in nickel. The solid curve was calculated from Eq. (4). The energy-loss data of Zucker et al. were converted to range data by extrapolating to zero. The energy-loss data of Roll and Steigert were fitted to the range curve at the point circled.

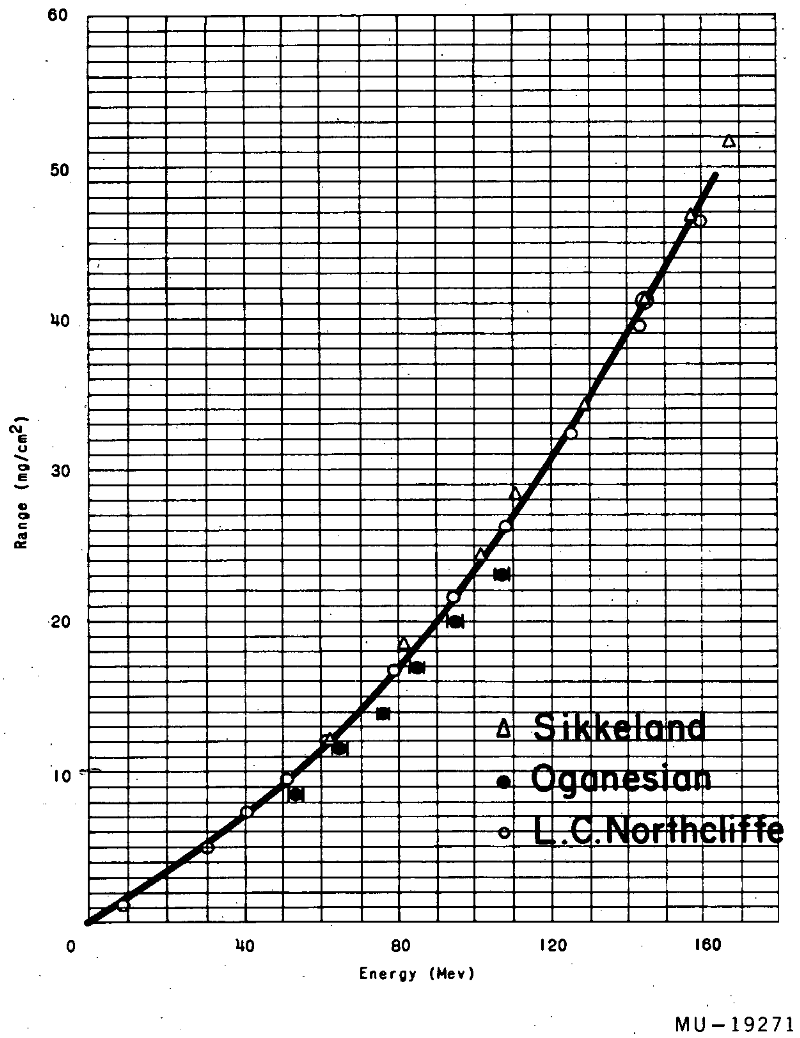


Fig. 13. Range-energy relation for $O^{16}$ ions in aluminum. The solid curve was calculated from Eq. (4). Sikkeland's energy-loss data were fitted to the calculated range curve at the point circled. Northcliffe's energy-loss data were converted into range data by extrapolating to zero.

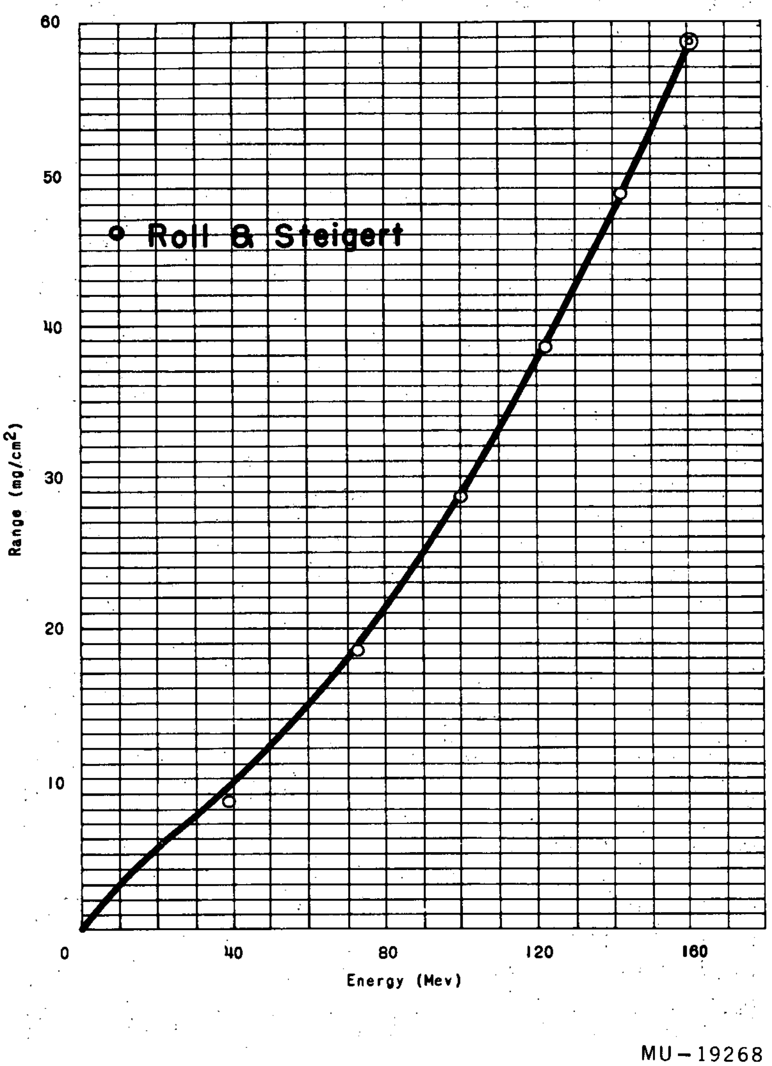


Fig. 14. Range-energy relation for $O^{16}$ ions in nickel. The solid curve was calculated from Eq. (4). The experimental energy-loss data of Roll and Steigert were fitted to the calculated range curve at the point circled.

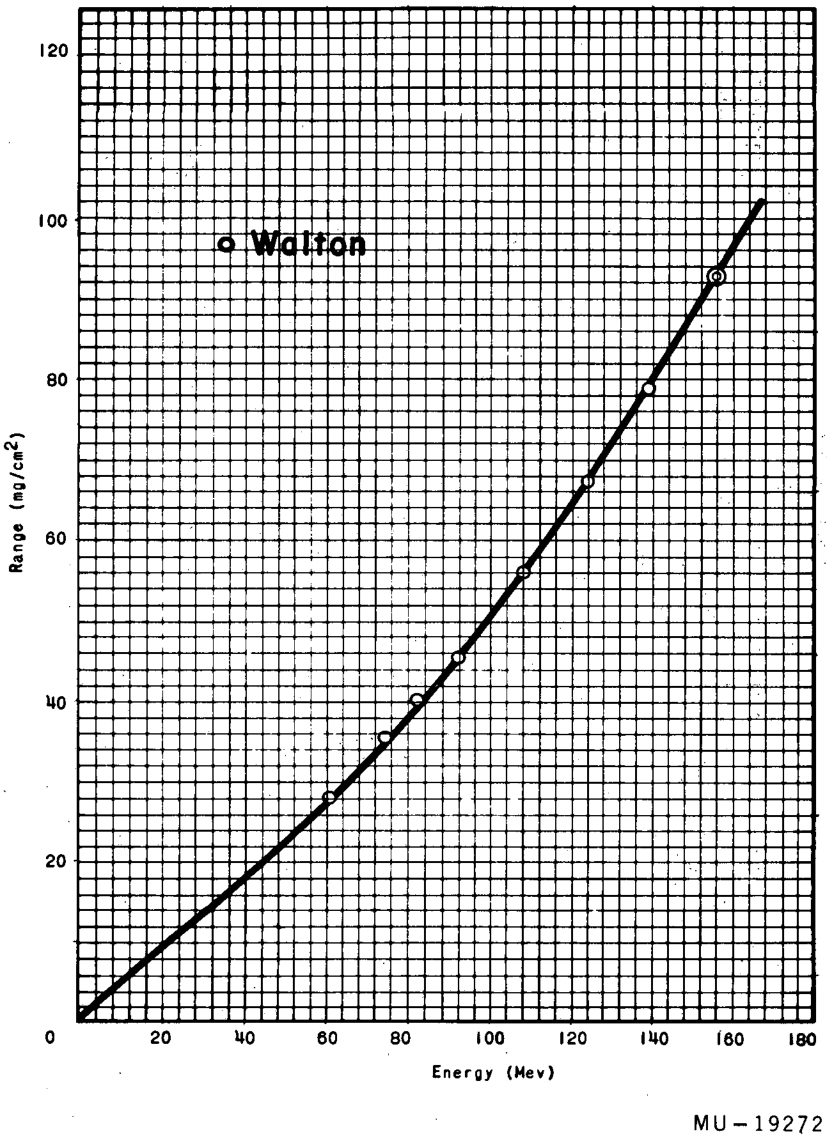


Fig. 15. Range-energy relation for $O^{16}$ ions in gold. The solid curve was calculated from Eq. (4). Walton's experimental energy-loss data were fitted to the calculated range curve at the point circled.

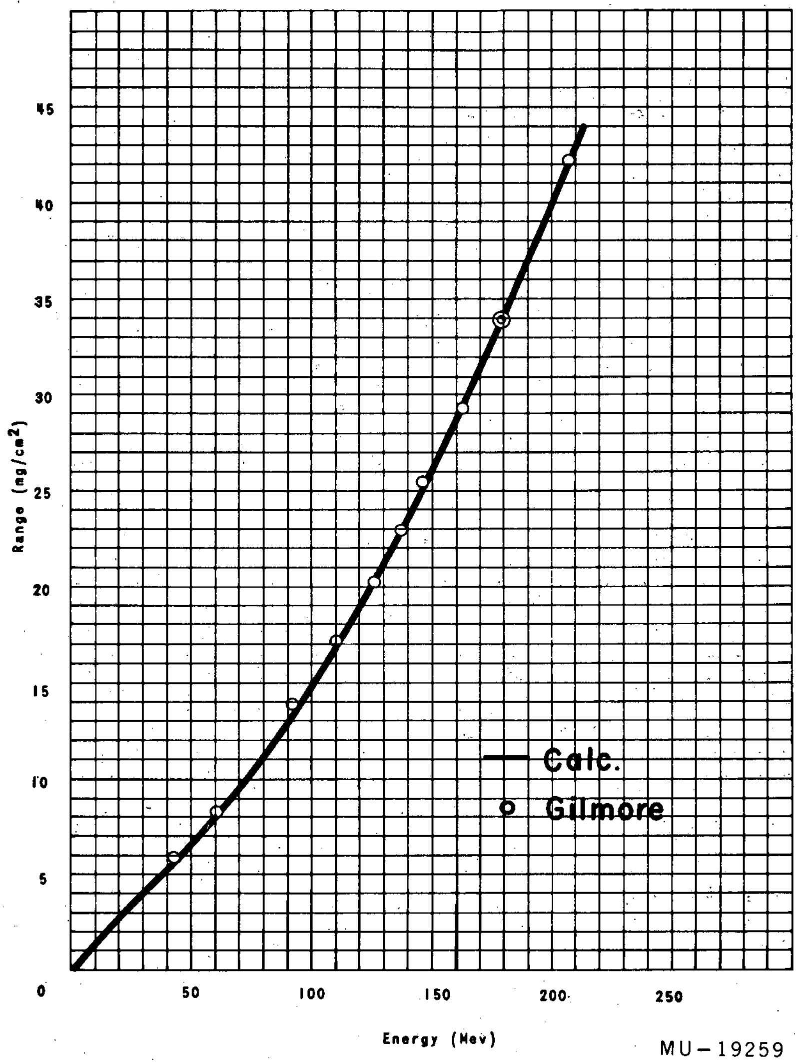


Fig. 16. Range-energy relation for $Ne^{20}$ ions in aluminum. The solid curve was calculated from Eq. (4). Gilmore's energy-loss data were fitted to the calculated range curve at the point circled.

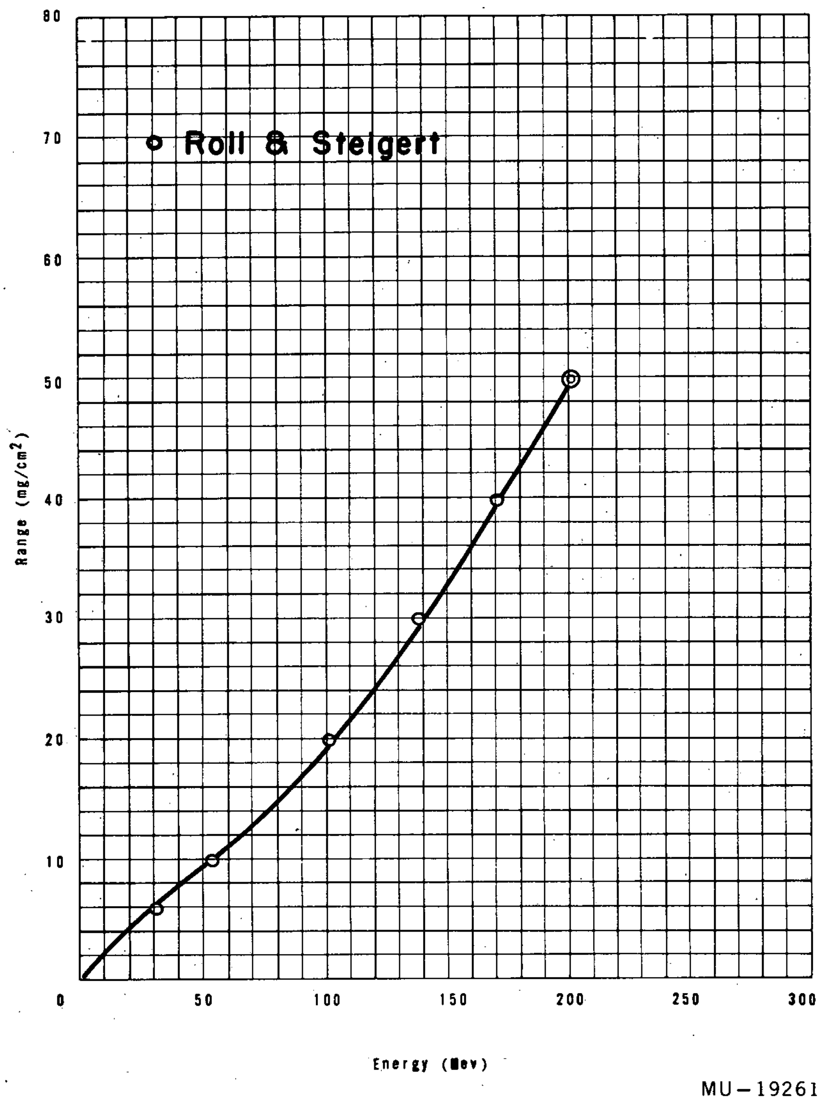


Fig. 17. Range-energy relation for $Ne^{20}$ ions in nickel. The solid curve was calculated from Eq. (4). The energy-loss data of Roll and Steigert were fitted to the calculated range curve at the point circled.