# Ranges of Protons in Medium and Heavy Elements

B. V. RYBAKOV

*Academy of Science, USSR*

We have measured the aluminum equivalents of the ranges of protons with energies 1-7 Mev in Fe, Cu, Mo, Cd, Sn, Ta and Pb. A method is presented for constructing an empirical range-energy curve on the basis of available data for all medium and heavy elements in the indicated range of energies.

## INTRODUCTION

I N the work of Vlasov and others [1] on the interaction of protons with tritons, protons are slowed to various energies by means of lead filters. There it is necessary, knowing the initial energy of the protons, to determine their energy after passing through a given thickness of lead. Up to this time there is lacking in the literature a sufficiently exact range-energy curve for Pb and other heavy and medium elements in the energy range 1-7 Mev. Reliable calculation of these curves on the basis of existing data on mean excitation potentials of atoms appears difficult, since the Bethe-Bloch formula, to which current theories of the passage of charged particles through matter lead, is correct only under the condition $E_p \gg (M/m) E_{el}$, which is poorly satisfied for heavy elements with protons whose energy is not large. (For Pb with protons of 1 Mev energy, it is not satisified for $K$-, $L$-, $M$- and $N$-electrons.) In connection with this we carried out measurements of the aluminum equivalents of the ranges of protons in Fe, Cu, Mo, Cd, Sn, Ta and Pb and constructed range-energy curves for these elements on the basis of the existing curve for $Al$ [2] .

## APPARATUS AND METHOD OF MEASUREMENT

The work was performed with a beam of protons of energy 7.3 Mev, brought out of a cyclotron into a vacuum channel and focused by a special magnet. At the focus of the magnet in the vacuum chamber was located a remote-control arrangement for placing in the path of the beam filters of the substances to be studied and measuring the proton current which passes through the filter and the proton current which is stopped by it. The schematic arrangement is shown in Fig. 1. A beam of
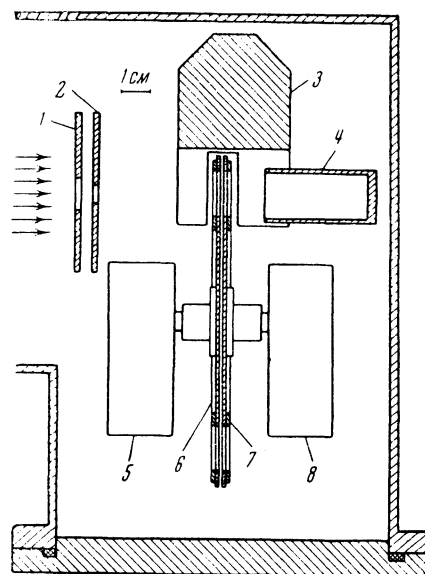


FIG. 1. Diagram of apparatus for measuring the aluminum equivalent of the range of protons in various substances. *1* and *2*-diaphragms; *3*-permanent magnet; the field is perpendicular to the plane of the figure; *4*-Faraday cylinder; *5* and *8*-remote controlled rotating mechanism; *6* and *7*-disc-shaped plate-holder with filters.

protons is collimated by diaphragms 1 and 2. Diaphragm 2 serves as trimmer for tuning the cyclotron. The diaphragms are kept at a potential of + 200 V, preventing secondary emission electrons from them from falling onto other parts of the equipment. The filters are placed in two disc-shaped plate-holders 6 and 7, with 12 in each. The discs are mounted on the axis of telephone searchers 5 and 8 and can be turned independently of one another into any of 12 positions. The permanent magnet 3 is intended to catch the secondary emission electrons from the filters. Under the action of the magnetic field it sets up, the electrons are either turned into the disc or fall on the magnet.

[1] N. A. Vlasov, C. P. Kalinin, A. A. Ogloblin, L. N. Samoilov, V. A. Sidorov, V. I. Chuev, J. Exper. Theoret. Phys. USSR **28**, 639 (1955)

Both the magnet and the discs are insulated from the body and connected together by sliding contacts. The charge collecting on this system determines the number of protons stopping in the filters. After passing through the filters the beam is completely stopped in a Faraday cylinder, the fore edge of which enters the gap between the poles of the magnet. The magnetic field does not permit secondary emission electrons to leave the cylinder.

The currents $I_1$ (from the Faraday cylinder) and $I_2$ (from the disc-magnet system) are measured by string electrometers by a constant deflection method in which readings of the two electrometers are taken simultaneously. The quantity $I_1/(I_1 + I_2)$ plotted in its dependence on the thickness of the filter is the usual absorption curve. The aluminum equivalents of the proton ranges are measured as follows. The absorption curve in aluminum is taken. Then, without turning off the beam, part of the aluminum in the end of the range is replaced by a specimen of the investigated substance and again an absorption curve is taken, in which the thickness of aluminum before the specimen is varied. The difference in the thickness of aluminum corresponding to the points of half absorption on these curves gives the aluminum equivalent of the specimen.

In Fig. 2 is shown one of the absorption curves of protons in Al. The mean range of the protons in Al, found from it as the thickness of aluminum absorbing half the protons, is 97.0 ±0.3 mg/cm$^2$. Using the range-energy curve of protons in Al [2] we find that the mean energy of the protons in the beam is 7.3 Mev. From the absorption curve it is also possible to estimate the energy spread of the beam. The differentiated curve, shown in the same figure, has a half-width consisting of 2% of the range. Subtracting from this the half-width due to straggling, the magnitude of which for Al is 1.3% for protons of 7.3 Mev energy [3], we find that the spread in proton energies about the mean value is ±0.07 Mev.

The mean energy of the protons fluctuated somewhat during the measurement. The error introduced by this in the magnitude of the aluminum equivalent does not exceed 0.4 mg/cm$^2$. (This figure also takes into account accidental errors in measuring the currents, as determined by the scatter of the point on the absorption curve.) It was observed that as a result of the cyclotron shutdown, during which the insulators of the deflection

plates and the filament of the ion source were changed, etc., the change in the mean energy of the protons in the beam could amount to 0.1 Mev. In the present case this is not significant since the measurement of the aluminum equivalent is carried out without turning off the beam.
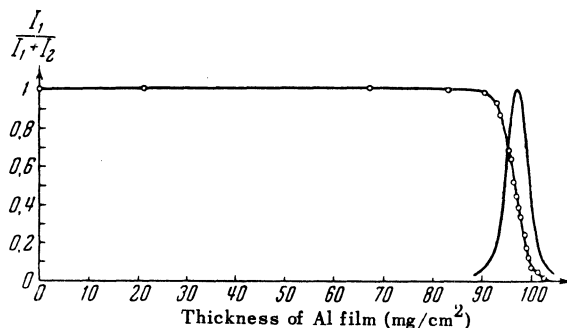


FIG. 2. Absorption curve of proton beam in Al.

The thickness of the filter in mg/cm$^2$ is determined from its area and weight. The following method was used to measure the area of the filters. A disc cut from the foil stock was clamped between two cylinders on the lathe and turned to a diameter of 25 mm which was measured by a micrometer to an accuracy of 0.01 mm, giving an error of less than 0.1% in the value of the area. The filter was weighed on an analytical balance with a precision of 0.1 mg. Thus the error in the mean thickness of the filter does not exceed 0.1 mg/cm$^2$. All the filters but molybdenum and tantalum were sufficiently uniform in thickness. The purities of the materials employed are as follows: Al – not less than 99.7%; Fe, Cu, Cd, Sn and Pb – not less than 99.8%; Mo and Ta – about 99.5%.

## RESULTS OF MEASUREMENT

In the Table is presented the range of protons in the investigated substance ($R$) and the equivalent of this range in aluminum ($R_{Al}$). The uncertainty in the determination of $R_{Al}$ is about ±0.5 mg/cm$^2$. For Mo and Ta it is somewhat more, since in these cases errors are introduced by nonuniformity of the foil. Determining the proton energies corresponding to the ranges $R$ from the range-energy curve for Al [1], it is possible to construct the range-energy curve for the investigated substances. This is presented in Fig. 3 (except for Cd, whose curve lies very close to that for Sn).

[2] J. H. Smith, Phys. Rev. **71**, 32 (1947)

[3] D. O. Caldwell, Phys. Rev. **88**, 131 (1952)
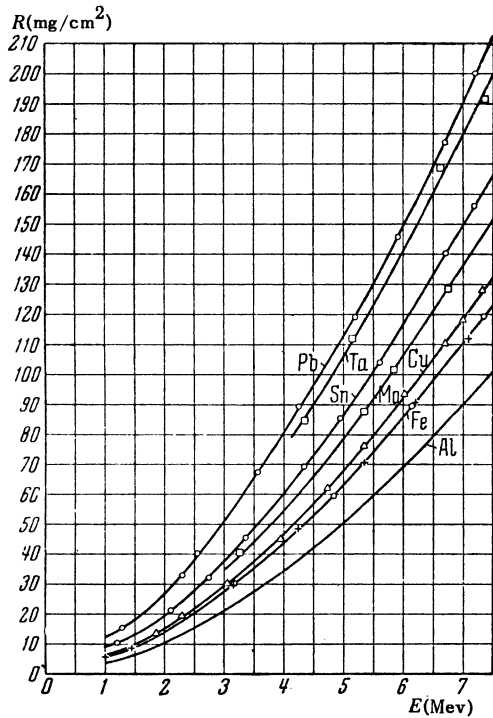
$R(\text{mg}/\text{cm}^2)$

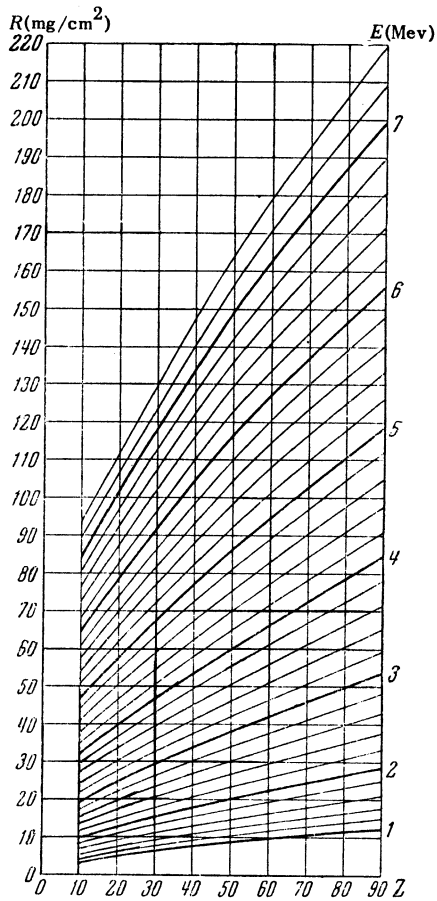FIG. 3. Range energy curve for protons in various elements.

FIG. 4. Nomogram for the determination of the path $R$ of protons with energies $E$ in an element of atomic number $Z$.

TABLE

| Element | $Z$ | $R$ (mg/cm2) | $R_{Al}$(mg/cm2) | Element | $Z$ | $R$ (mg/cm2) | $R_{Al}$(mg/cm2) |
|---|---|---|---|---|---|---|---|
| Fe | 26 | 5,3 | 3,5* | Cd | 48 | 48,2 | 28,3 |
| | | 8,8 | 6,5* | | | 64,2 | 37,6 |
| | | 29,5 | 23,0* | | | 86,4 | 52,2 |
| | | 30,1 | 23,3 | | | 105,2 | 63,0 |
| | | 48,1 | 38,2* | | | 130,2 | 79,6 |
| | | 59,7 | 47,9 | Sn | 50 | 10,2 | 4,7 |
| | | 70,5 | 57,5* | | | 21,3 | 11,9 |
| | | 89,3 | 72,6 | | | 32,2 | 18,1 |
| | | 90,5 | 73,2* | | | 45,6 | 25,8 |
| | | 112,0 | 92,0* | | | 69,0 | 39,9 |
| | | 118,8 | 98,1 | | | 85,4 | 49,8 |
| Cu | 29 | 13,4 | 9,8 | | | 104,1 | 61,8 |
| | | 19,4 | 13,6 | | | 140,2 | 84,2 |
| | | 30,1 | 21,7 | | | 155,7 | 94,0 |
| | | 44,8 | 33,5 | Ta | 73 | 84,7 | 40,0 |
| | | 62,0 | 45,8 | | | 112,0 | 53,0 |
| | | 75,8 | 65,8 | | | 169,0 | 82,1 |
| | | 93,5 | 70,6 | | | 191,5 | 98,5 |
| | | 110,2 | 83,4 | Pb | 82 | 15,3 | 5,4 |
| | | 117,8 | 90,0 | | | 32,9 | 13,5 |
| | | 127,8 | 97,3 | | | 40,2 | 16,1 |
| Mo | 42 | 40,6 | 24,4 | | | 67,4 | 28,5 |
| | | 87,8 | 65,4 | | | 89,6 | 38,4 |
| | | 101,8 | 66,0 | | | 118,8 | 53,9 |
| | | 128,5 | 84,0 | | | 145,6 | 67,6 |
| Cd | 48 | 8,9 | 4,3 | | | 177,1 | 84,0 |
| | | 19,7 | 10,5 | | | 200,0 | 94,8 |
| | | 31,2 | 17,4 | | | | |

* In these cases measurements were carried out on beams of deuterons with energies 14.7 mev. The paths for the protons were computed with the aid of the well-known relation:
$$R_p(E) = \tfrac{1}{2} R_d(2E).$$

Having the experimental data for the proton ranges in several elements with atomic numbers $Z$ from 13 to 82 makes it possible to construct empirical range-energy curves for all intermediate elements. As was to be expected, the curve of range versus atomic number at given proton energy is rather smooth for many-electron atoms. Because of this it is possible by graphing the ranges we obtained in their dependence on $Z$ for given proton energies, to find by graphical interpolation the ranges in the intermediate elements. A nomogram constructed in this way is presented in Fig. 4. This nomogram is used to determine the ranges of protons with energies from 1 to 7.4 Mev in any element with $Z > 10$. For all values of the range, the uncertainty connected with the precision of the measurements performed by us is about 0.5 mg/cm2 . To this uncertainty must be added an error of about 1% connected with the precision of the range-energy curve for Al[2] , and an error of 1-2% caused by irregularities in the dependence of $R(Z)$ (decreasing with increasing $Z$).

In conclusion we tender our deep thanks to N. A. Vlasov and S. P. Kalinin for guidance and constant help in this work, and to V. I. Vernashevskii for taking part in the construction of the apparatus.