Proton Stopping Power of Solid Beryllium

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The energy loss of protons penetrating beryllium foils of different thicknesses has been determined as a function of the proton energy by measuring the shift of those potentials at which a thin aluminum target gives resonance radiation. The experimental points fit within ± 2 percent a theoretical curve corresponding to an average ionization energy of 64 ± 5 ev, which is in agreement with a recent theory for the stopping power of metals.

THE sharp resonances for proton capture by light nuclei offer a convenient means for analyzing the energy distribution of a beam of protons, and the phenomenon may thus be used to make accurate measurements of the energy loss suffered by protons passing through matter by inserting thin foils in a homogeneous proton beam before it reaches the target.

The theory of the stopping power of metals has recently been discussed,[1,2] and therefore, it appeared of interest to apply the method of determining the specific stopping power of protons in beryllium, because of the high relative number of conduction electrons in this metal and because it is well suited for the preparation of thin foils.

Aluminum was chosen as target material, because its spectrum was well known from an earlier investigation at this institute.[3] The technique and apparatus for the production of the proton beam and for the detection of the gamma-radiation were those described in the work mentioned.

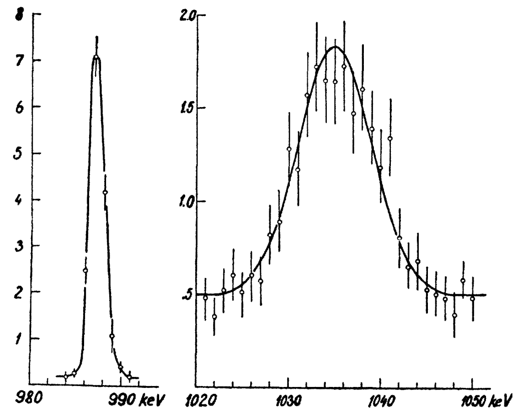

FIG. 1. The 986 kev Al resonance measured (a) without foil, and (b) with a 0.22 mg per cm² Be foil inserted in the proton beam. The ordinates give the γ-ray yield in the same arbitrary unit.

A small disk with six circular openings, three of which were covered by beryllium foils, was mounted in the acceleration tube at a height of 35 cm above the aluminum target. By the help of a small magnet the different openings of the disk could be brought into the path of the protons.

The proton current used was of the order of 0.2 microamp and the width of the beam was 3 mm. Counting was only allowed by means of an electronic switch,[3] when the fluctuations of the acceleration voltage were smaller than ± 2 kv. The different aluminum targets used had stopping powers of 1 to 10 kev.

The foils had been prepared by evaporation and the total contamination of other metals was found by a spectral analysis to be less than 0.1 percent.[4] A possible oxidation of the surface of the foils would be insignificant for the present purpose, since the stopping power of oxygen per weight is very nearly equal to that of beryllium.

The areas of the foils were calculated from measurements with a traveling microscope and their weights were determined with a microbalance. The thicknesses obtained in this way are supposed to be correct within ± 1 percent. After the measurements of the stopping power, the thicknesses of the foils were checked and found to be unchanged within this limit.

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[1] H. A. Kramers, Physica **13**, 401 (1947).
[2] Aage Bohr, Kgl. Danske Vid. Selsk. Mat.-fys. Medd. (in press).
[3] K. J. Broström, T. Huus, and R. Tangen, Phys. Rev. **71**, 661 (1947).
[4] We are most indebted to civil engineer Mr. Kühnel-Hagen for carrying out this analysis.

As an example of the measurements of the stopping power, Fig. 1 shows the aluminum resonance at 986 kev measured without foil, and with a foil of thickness 0.222 mg per cm^2 inserted in the proton beam. The difference between the mean energies for the two curves has been taken as the energy loss of the protons.

The standard deviation is seen to be 4 to 5 kev and 1 to 2 kev with and without foil, respectively. It is of interest that this broadening effect just corresponds to the theoretical estimate of the straggling.[5] The same is the case with the other foils, and it is likely, therefore, that inhomogenities in the foils do not contribute essentially to the broadening. The precision should thus approach the limit given by the straggling.

In Fig. 2 are plotted the experimental values of the specific stopping power 's' obtained with three foils of thicknesses 0.609 (crosses), 0.245 (circles) and 0.222 (dots) mg per cm^2 as a function of the average energy of the protons in the foil.

The theoretical curves are drawn according to the formula:[6]

$$s=\frac{2\pi e^4}{E\mu}\frac{Z}{A}\left(\log\frac{4E}{I_{av}}\frac{\mu}{M}-\frac{C_k(E)}{Z}\right)$$

with the average ionization energy I_{av} of the electrons in the beryllium atoms as a parameter. E is the energy, and M the mass of the protons, e, the charge, and μ the mass of an electron, and Z the atomic number and A the mass number of beryllium. C_k is a correction, which is due to the strong binding of the K electrons.[6]

It is seen that the experimental points fit with a curve corresponding to I_{av} equal to 64 ± 5 ev. The theoretical value of I_{av} for the metallic state of beryllium has been estimated to be about 60 ev,[2] whereas the value of I_{av} for separated beryllium atoms would be only about 45 ev. The measurements thus confirm the predicted increase in I_{av} for the metallic state, which is to be ascribed to the mutual interaction of the electrons in the substance. This effect, which is especially pronounced in beryllium with its high electron density, implies, in fact, a screening of the field of the moving particle and thus gives rise to a decrease in the stopping power.

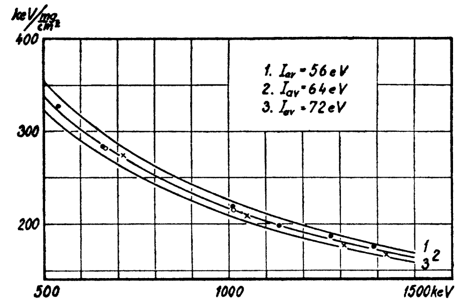

Fig. 2. The specific stopping power for protons on metallic Be measured with foils of thicknesses 0.222 (dots), 0.245 (circles) and 0.609 (crosses) mg per cm^2.

It may be added, that the earlier theory of v. Weizsäcker[7] of the stopping power of metals, in which the conductivity was assumed to play a decisive role, gives a value for I_{av} of the order of 10 ev.

In conclusion we wish to thank Professor Niels Bohr for his continuous interest in this work, and mag. scient. Aage Bohr for suggesting the investigation. Our thanks are also due to cand. mag. K. J. Broström and mag. scient. Torben Huus for their advice in experimental questions.

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[5] See N. Bohr, Kgl. Danske Vid. Selsk. Mat.-fys. Medd. **18**, 8 (1948).

[6] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 264 (1937).

[7] C. F. v. Weizsäcker, Ann. d. Physik **5**, 17, 869 (1933).