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ON THE STOPPING POWER OF LITHIUM FOR α-RAYS

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The stopping power of a substance for α-rays depends according to Bohr's theory on the number of electrons in the atom, and the frequencies of the vibrations, about their positions of equilibrium or stationary motions, which the electrons perform when they are removed from these by external forces. Due to the simplifying assumptions introduced in the calculations, however, the theoretical expressions may not be expected to offer a close approximation unless the velocities of the electrons in their stationary orbits are small compared with the velocities of the α-rays, a condition which is fulfilled only for atoms of elements with low atomic number.[1] As regards the experimental data concerning such elements accurate measurements are at hand of the stopping power of hydrogen and helium for α-rays, which have been found to be in close agreement with the theory. For a closer test of the theory it is desirable, however, to possess measurements also of the stopping power of lithium, and it will also be expected, that it may be possible by means of such measurements to obtain a test of the theoretical conceptions of the constitution of the lithium atom, affording interpretations of the spectral and chemical properties of this element. On the proposal of Professor Bohr we have therefore undertaken an experimental investigation of the stopping power of lithium for α-rays.[2]

[1] N. Bohr, Phil. Mag. XXX. S. 588, 1915.

[2] When the present investigation was in progress measurements of

§ 1. Methods of investigation.

The stopping power was determined by measuring the change in the range of a beam of α-rays from radium C, produced by sending the beam through a thin sheet of metallic lithium pressed out between two mica foils. The press used for the production of the lithium-mica preparate was designed by Professor Bohr and had the shape shown in the fig. 1, in which the left half shows the exterior appearance of the apparatus, and the right half shows the interior in section.

The whole press was made of iron and steel and consisted in the main of an iron tube T, to the ends of which were fastened two iron fittings which acted as guides for two pistons P_1 and P_2 of hard steel which could be moved in the direction of the axes of the tube by means of two screws S_1 and S_2, the pressure being transferred to the pistons by means of the two small steel balls B_1 and B_2. Besides the tube was provided with a fitting F, forming a small auxiliary press in which the lower end of the screw A acted as a piston fitting tight in a cylindary tube, the lower end of which was closed by a steel disc D with a small conical hole through its centre. Further the press was

the ranges of α-particles in a large number of elements, including lithium, have been published by H. Rausch von Traubenberg (Phys. ZS. XXI. S. 588, 1920). These measurements are performed by means of a very elegant method, by which the range is measured by examining the place on a wedgeshaped plate of the substance, where the α-rays are just able to penetrate through it. The accuracy which may be obtained by this method is not directly stated by v. Traubenberg, and is hardly very large for an active substance like lithium, the surface of which must be protected against the action of the air. Quite apart from the valuable survey over the stopping powers for α-rays of a large number of substances, contained in the paper mentioned, it can not therefore be said to dispense with the want in consideration of which the present investigation was undertaken.

provided with a small glass window *W* and two short tubes by which a stream of gas could be led through it, and of which one, *H*, fastened to the main tube of the press opposite the fitting *F*, is shown at the figure.

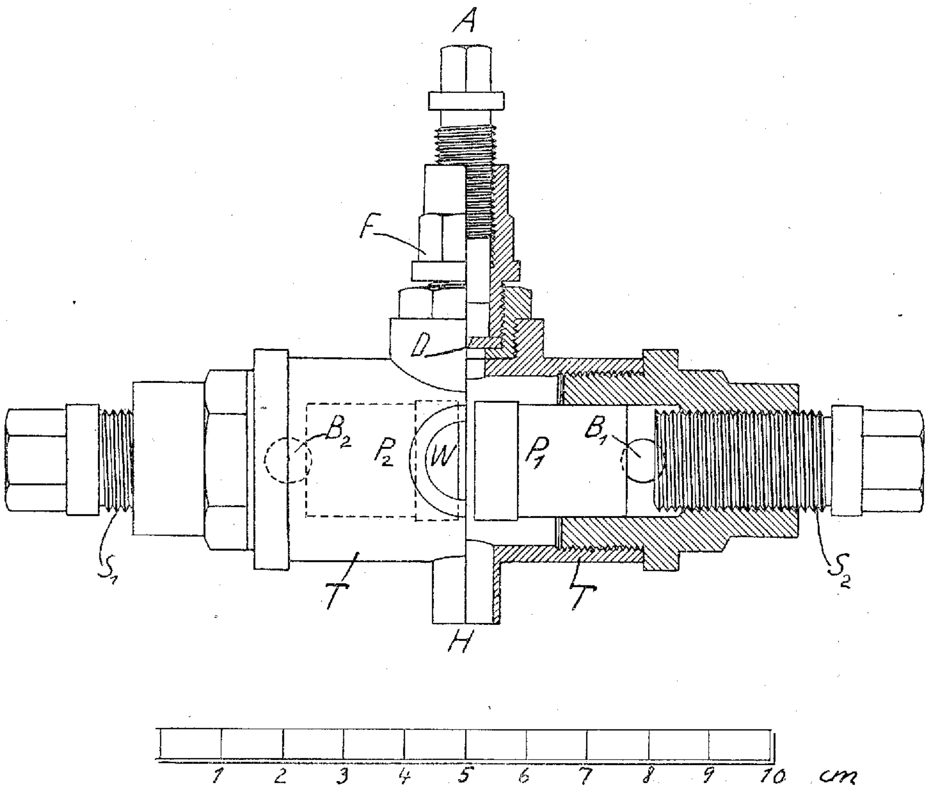

Fig. 1.

The proceedure in producing a lithium-mica preparate was the following: A lump of metallic lithium was placed under the screw shown at the top of the figure and a lithium wire with diameter of about half a millimeter was formed by the soft metal protruding through the small hole in the disc *D*, when the piston was screwed down. This wire was led down between the plane front surfaces of the pistons P_1 and P_2 and out of the tube H and streched by a suitable tension, before it was pressed out to a sheet by forcing together the pistons P_1 and P_2 to the plane surface of each of which a thin mica foil was fastened by means of a drop of parafine oil before bringing in the lithium in the apparatus. This allowed the lithium-mica preparate to be easily removed from the press after the loosening of the screws S_1 and S_2. The whole procedure of the production of the wire, its stretching and outpressing could be watched through the window W. During the procedure a current of dry nitrogen or dry air was sent through the apparatus. Dry atmospheric air affects lithium only very slowly, so that a fresh cut lithium surface may remain bright even for several months, when kept over phosphorous pentoxide.. The lithium sheets pressed out between the mica foils kept a complete bright and clean surface within the time intervals which came into consideration for their examination. The press was very carefully constructed, and the lithium-mica preparates produced showed as a rule a very regular behaviour as regards their stopping power for α-rays. Only in a few cases the ionisation curves showed a shape, suggesting that the lithium sheet was not quite uniform, the cause of which, however, might also have been due to a splinter sprung from one of the mica foils during the pressing.

The apparatus for measuring the change in the range of the α-rays, when sent through the lithium-mica preparate, is shown in section in fig. 2. It consists of a wide glass tube T, to the ends of which two brass rings which carried the radioactive source and the ionisation chamber were fastened by means of sealing wax. The radioactive material was deposited at the end of an iron cone C, which could be made to fit airtight into a hollow cone H fastened to the lower brass ring, as well as into a similar cone fastened to a glass reservoir connected with a plant of radium emanation, in which the iron cone could be activated by exposure to the emanation. The lithium preparate was placed over the radioactive source on a brass disc, which could be turned round a vertical axis and which is shown in vertical projection to the right of the main figure. In this disc were two holes; above the first the preparate was applied, and above the second two mica foils of the same specimen as used for protection of the lithium sheet. To the brass disc was fastened an iron rod, shown in black in the sectional figure, which made it possible to turn the plate from the outside by means of a magnet.

The construction of the ionisation chamber, fastened to the upper brass ring, is also seen from this figure; the hatched parts indicate brass, the dotted ebonite. G is a fine metal wire gauze which through the metal wire W_1 is connected with a source of constant high potential, and which forms the lower border of the ionisation chamber, the upper border of which is formed by the brass plug K, which through the rod S and the metal wire W_2 is connected with a quadrant electrometer. K was insulated from the other metal parts by the ebonite plate E, which at the same time closed the apparatus airtight, being pressed down against a plane by means of a screw forming the lower part of a hollow cylinder, protecting S from electrostatic disturbances. The whole ionisation chamber could easily be dismounted, when the surfaces of the ebonite parts wanted cleaning. During the measurements the air in the apparatus was renewed with suitable intervals through the two tubes R_1 and R_2 in order to remove eventual traces of emanation yielded from the

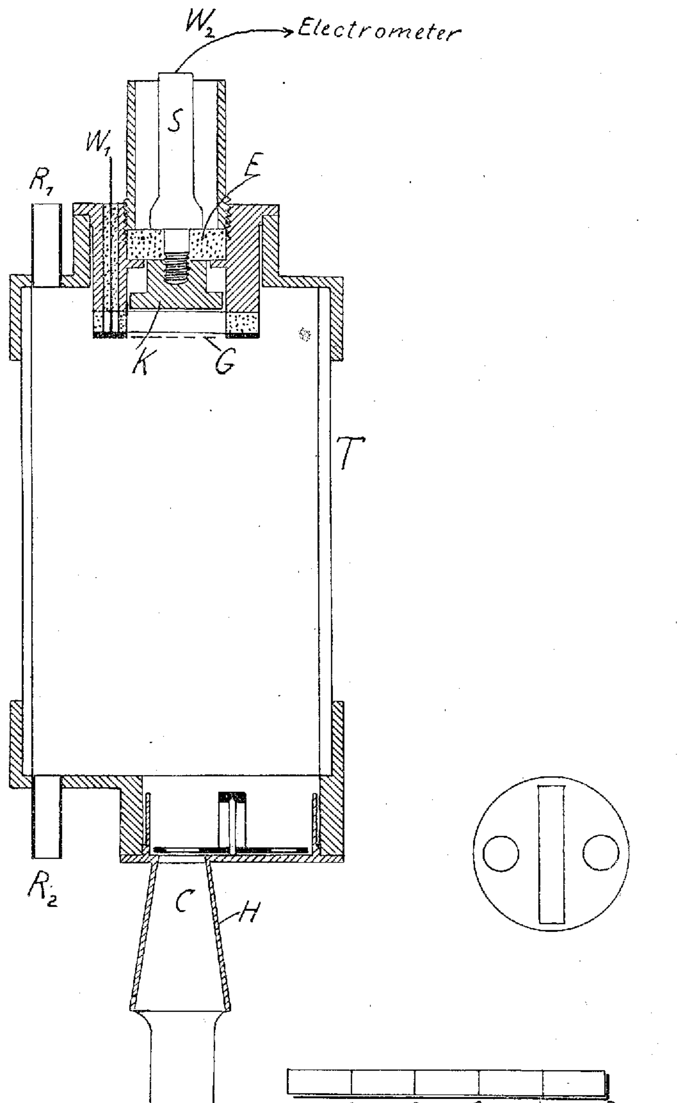

Fig. 2.

surface of the iron cone, on which the radioactive material was deposited. The β-rays were deflected by a magnet.

By varying the pressure in the apparatus the various parts of the path of the α-rays could be brought to fall within the ionisation chamber. If by the pressure p and the relative activity A the rate of charging, measured by the quadrant electrometer, is i, the quantity $I = \frac{i}{p \cdot A}$ will be a measure for the ionisation at the pressure 1 and the activity 1. If on a diagram I is represented as ordinate and p as abscissa, we get a curve of the same type as the well-known ionisationcurve of Bragg. The determination of the stopping power of the lithium sheet was now obtained by drawing curves partly with the lithium preparate introduced in the beam of α-rays, partly with introduction of two mica foils of the same specimen used at the production of the preparate, the horizontal distance d between the middle points of the steeply falling parts of the two curves, determining the air equivalent of the lithium sheet. The air equivalent referred to a pressure of 76 cm Hg and 0° C will clearly be given by $Eq = \frac{d \cdot l \cdot 273}{76 \cdot (273 + t)}$, where l is the distance between the source of rays and the centre of the ionisation chamber, and where t is the temperature. In the actual apparatus l, measured from the upper plane surface of the activated iron cone to the plane lying in the middle between the gauze G and the surface of the brass plug K, was equal to 9,25 cm, while the temperature during the experiments was about 18 degrees. From the air equivalent the corresponding hydrogen equivalent was next calculated by means of Taylor's measurements.[1] Now, according to these measurements the relative stopping power of different substances is not quite independent of what part of the path of the range these substances are placed. In the experiments

[1] Taylor, Phil. Mag. XVIII, 604, 1909.

the air equivalent of the lithium-mica preparate was about 4 cm, giving a mean value of about 5 cm for the range in air of the rays when passing through the lithium sheet. The relative stopping power of lithium and hydrogen deduced in the experiments may therefore be taken as corresponding to α-rays of a range in air of about 5 cm which according to measurements of Geiger[2] corresponds to a velocity of about $1{,}8 \cdot 10^9$ cm.

In order to find the ratio between the atomic stopping power of lithium and hydrogen we must next know the amount of lithium present per cm^2 of the preparate. In order to determine this amount a circular disc with a diameter of about 5 mm was cut out of the lithium-mica preparate by means of a hollow punch. Placing this disc in boiled distilled water in a quarts retort the lithium was dissolved and the amount of lithium hydroxyd next measured by titration with hydrochloric acid.

§ 2. Results of the measurements.

The following data may serve as an example of the results of the measurements, described in the preceding chapter. In fig. 3 three ionisation curves *I*, *II* and *III* are represented, where *I* is obtained with the lithium-mica preparate, and *II* with two mica foils of same specimen while *III* is obtained before the introduction of the stopping sheets. The mean distance between the steep parts of the curves *I* and *II* was found to correspond to a pressure of 12,70 cm *Hg*, giving for the air equivalent of the lithium sheet, according to the formula indicated on p. 9, $Eq = \frac{9{,}25 \cdot 12{,}70 \cdot 273}{76{,}00 \cdot 289} = 1{,}50$ cm air. Next, a layer of air of thickness 1,50 cm at 76 cm *Hg* and $0^\circ C$ has for α-rays with a

[1] H. Geiger, Proc. Roy. Soc. XXXIII, 505, 1910.

range of about 5 cm according to the measurements of Taylor a hydrogen equivalent of 6,08 cm, corresponding to $N_H = \frac{2 \cdot 6{,}08}{22{,}4 \cdot 1000} = 5{,}43 \cdot 10^{-4}$ gram atoms of hydrogen per cm². As regards the determination of the amount of lithium

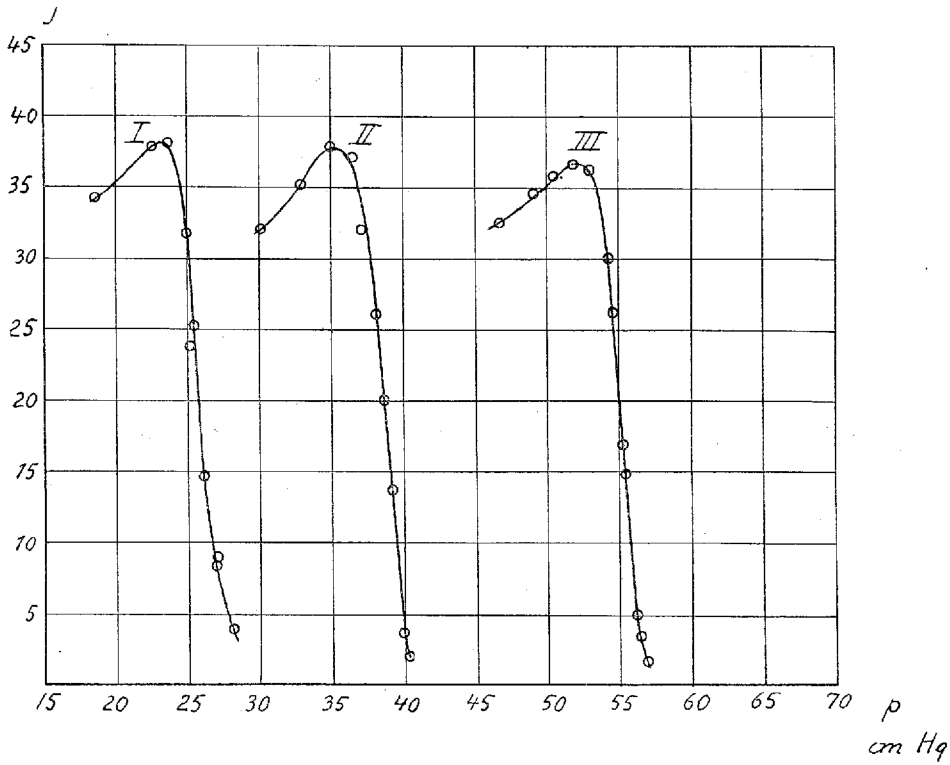

Fig. 3.

present per unit area of the preparate, the area of the disc punched out was found to be 0,215 cm² and after solving in water 2,375 cm³ hydrochloric acid (0,0199 n) was claimed for the neutralisation of the solution. This gives for the preparate the presence of $N_{Li} = \frac{2{,}275 \cdot 0{,}0199}{0{,}215 \cdot 1000} = 2{,}20 \cdot 10^{-4}$ gram-atoms of Lithium per cm². Assuming a specific weight of 0,55, this gives for the thickness of the lithium sheet, pressed out between the mica foils ca. 0,002 cm; The accurate knowledge of this thickness, however, is not essential for the present determination of the relative stopping power. In fact, from the above data this quantity is found as the ratio between N_{Li} and N_H, which in the experiment under consideration gives for the relative stopping power $N_{Li} : N_H = 5{,}43 : 2{,}20 = 2{,}47 : 1$.

The results of four complete experiments of this kind with different lithium preparates gave:

Air equivalent of *Li* sheet	*H*-atoms per cm² of equivalent sheet	*Li*-atoms per cm² of preparate	Ratio between atomic stopping power of *Li* and *H*
1,32 cm	$0{,}492 \cdot 10^{-3}$	$0{,}207 \cdot 10^{-3}$	2,38
1,58 —	587	239	2,46
1,46 —	543	220	2,47
1,55 —	577	228	2,53
		mean	2,46

As regards the accuracy of the results we estimate the uncertainty of the single determination of the air equivalent to be about 3⁰/₀, and also that the further error introduced in the calculation of the hydrogen equivalent amounts to no more than 2⁰/₀. The uncertainty of the mean value of the final results may therefore be estimated to amount to a few per cents. As regards the purity of the lithium, the specimen used was "Li. met. pur." from Kahlbaum, and a chemical analysis kindly performed by Lektor Bjørn-Andersen gave as impurities present 0,35⁰/₀ *Na*, about 0,5⁰/₀ *Fe* and perhaps a little *Al*. For the estimate of the influence of these small impurities on the result we may consider not only their direct effect on the stopping power of the lithium preparate, but also their effect on the titration of the lithium sheet, which effects partly compensate each other. Thus we may estimate in the following way, how much the presence of the iron alters the result. Let the number of gram atom of lithium per cm^2 be x_1 and of iron x_2, and let the atomic stopping power of lithium in proportion to hydrogen be n_1 and of iron n_2; the measured stopping power will then be

$$\frac{n_1 x_1 + n_2 x_2}{x_1 + 3x_2} \backsim n_1 + \frac{x_2}{x_1}(n_2 - 3n_1)$$

where the second member on the right side indicates the error in the result. Putting now $n_1 = 2{,}5$ and according to the measurements of R. v. Traubenberg $n_2 = 9{,}5$, and further, corresponding to the presence of 0,5% iron, $\frac{x_2}{x_1} = \frac{7}{55} \cdot \frac{1}{200} = \frac{1}{1600}$, we get for this error $\frac{9{,}5 - 7{,}5}{1600} = \frac{1}{800}$, or a value several times smaller than the uncertainty of the measurements as indicated above. In a similar way it can be shown, that the influence of 0,35% *Na* is minimal, and that the mentioned impurities will consequently have no sensible influence on the result of the present investigation.

As regards the experiments of Rausch von Traubenberg, referred to in the note on page 4, the accuracy seems as mentioned difficult to estimate. The range for α-particles from radium C in lithium, which was found to be 0,0129 cm, gives for the ratio between the atomic stopping power of lithium and hydrogen a value between 2,5 and 2,7 according to the value used for the specific gravity of lithium, which by various experimentators is given as lying between 0,59 and 0,54.

§ 3. Comparison with the theory.

The theory of Bohr leads to the following formula:

$$\frac{dV}{dx} = A \cdot \sum_{s=1}^{s=r} \log_{nat} B_s$$

where r is the number of electrons in the atom, and where

$$A = -\frac{4\pi e^2 E^2 N}{m M V^3}; \; B_s = \frac{V^3 \cdot k \cdot M \cdot m}{n_s \cdot e \cdot E (M+m)}$$

E and e denote the charge of an α-particle and an electron respectively, M and m their masses, N the number of atoms in unit volume and V the velocity of the α-particles. Moreover n_s denotes the frequency of vibrations, which one of the electrons in the atom performs when removed from its position of equilibrium or stationary orbit.

For hydrogen, where r is equal to 1, we get for an α-particle with velocity $1{,}8 \cdot 10^9$ cm sec, when, corresponding to atmospheric pressure and 20°, we put $\frac{N}{2} = 2{,}59 \cdot 10^{19}$ and for n_s introduce the value for the frequency of vibration of the electron in the atom, deduced from experiments on dispersion of hydrogen,

$$A = 3{,}89 \cdot 10^6 \quad \log_{\text{nat}} B_H = 6{,}37$$

which gives

$$\frac{dV}{dx} = -2{,}48 \cdot 10^7,$$

a value, which agrees very well with the values, which are determined by interpolation from the measurements of Geiger and Taylor, which with a close approximation for the mentioned velocity gives:

$$\frac{dV}{dx} = -2{,}5 \cdot 10^7.$$

As regards this agreement it may be noticed, that even a considerable change of n has only a small influence on the result; for instance $\frac{dV}{dx}$ will only be altered by 10%, if n is altered by a factor 2; a circumstance of essential importance for the application of the theory, because the value to be introduced for n is difficult to fix with any great accuracy.[1]

Asking next for a theoretical estimate of the ratio f between the atomic stopping powers in Lithium and in Hydrogen, we need only consider the ratio between the characteristic frequencies of vibration of the three electrons in the lithium atom and the frequency of the electron in the hydrogen atom. In fact, if the frequencies of the electrons in the lithium atom are denoted by $n_1 = x_1 n$, $n_2 = x_2 n$, $n_3 = x_3 n$ respectively, where n is the frequency of the electron in the hydrogen atom, we get

$$f = \frac{dV}{dx_{Li}} : \frac{dV}{dx_H} = 3 - \frac{\log_{nat} x_1 x_2 x_3}{\log_{nat} B_H}$$

or

$$f = 3 - \frac{1}{6{,}37} \cdot \log_{nat} x_1 \cdot x_2 \cdot x_3.$$

As regards the values of the frequencies n_1, n_2, n_3, we possess no direct evidence, for instance from measurements of dispersion in Lithium vapour. We must expect, that the ratios x_1, x_2, x_3 with approximation will be equal to the ratios between the frequency of revolutions of the electrons in the lithium atom and the frequency of revolution of the electron in the hydrogen atom, which ratios may be supposed to be known with considerable accuracy from recent work on atomic constitution. Thus we may suppose, that the two of the three lithium electrons will move in orbits, small in proportion to that of the hydrogen electron and will possess frequencies of revolution, which are about 8 times greater than the frequency of revolution of the hydrogen electron. The third electron in a neutral

[1] Compare N. Bohr, Phil. Mag. XXV, 23, 1913.

isolated atom in its normal state may on the other hand be supposed to move in an orbit larger than that of the hydrogen atom and to have a frequency of revolution about 4 times smaller. This gives approximately

$$x_1 x_2 x_3 = 8 \cdot 8 \cdot \tfrac{1}{4} = 16$$

and consequently

$$\log_{nat} x_1 x_2 x_3 = 2{,}77$$

from which we get $f = 2{,}56$ a value which within the accurary of the measurements agrees with the experimental value $f = 2{,}46$.

Considering this result we notice in the first instance, that the accurary of experiments is not great enough, by means of the given formulæ, to determine the quantity $x_1 x_2 x_3$ with an approximation amounting to more than a factor 2. On the other hand the approximative character of the theory would also hardly make it legitimate to assign a definite meaning to an attempt of evaluating this quantity more accurately. Nevertheless it will be seen, that the comparison of the results of the experiments with the theory offers a very direct support for the conclusion, that in spite of the loose binding of the valency electron, the electrons of the lithium atom are "in mean" considerably stronger bound than the electron in the hydrogen atom, such as we must expect from the theory of atomic structure.

Concluding remarks.

The stopping power of lithium for α-rays was determined by measuring the change in the range of the rays produced by penetrating through a thin sheet of metallic lithium, pressed out between two mica foils. The ratio between the stopping power of a lithium atom and a hydrogen atom was found with an uncertainty of a few per cent to be 2,46; a value which is in good agreement with Bohr's theory,

The investigations dealt with in this paper were performed at the physical laboratory of the polytechnical college of Copenhagen. On the completion of the work we wish to thank all those, who have assisted us during the experiments, above all Professor Bohr for much valuable advice, Professor Prytz for the permission to use the apparatus of the laboratory, Lektor Bjørn-Andersen for the execution of the chemical analysis of the lithium employed, and Professor Salomonsen for the permission to make use of the radium preparate.

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