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A HIGH INTENSITY MASS-SPECTROGRAPH FOR EXPERIMENTS ON THE SEPARATION OF ISOTOPES

BY

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Introduction.

In recent years a great number of different methods for the separation of isotopes has been developed. This technique has assumed increasing importance, the entirely or partly separated isotopes being used more and more in experimental investigations in both nuclear physics, spectroscopy, and biology.

Among the different methods the mass-spectrographic separation of isotopes holds a special position, inasmuch as by this means it is possible to produce extremely pure samples, the quantities separated, however, being exceedingly small.[1]

Only very few elements, however, have been subjected to mass-spectrographic separation. In the first place the alkalis Li, K, and Rb must be mentioned (Na and Cs possess only one stable isotope each, cf. 5, 17, 18, 19, 20, 21, 22, 23, 27). This is due to the fact that for the production of alkali ions especially efficient ion sources are available, the ions evaporating at thermal energies from a hot equipotential surface (8, 11, 24). Next, using a low voltage arc of special design it has been possible to produce samples of the pure boron isotopes ^{10}B and ^{11}B and of the carbon isotope ^{12}C (27).[2]

For all these experiments special apparatus (high intensity mass-spectrographs) have been used which on many points differ materially from the well-known high precision mass-spec-

[1] In a treatise by J. Koch, *Mass-Spectrographic Separation of Isotopes. With a Special View to the Production of Isotopes for Experimental Research*, these methods have been subjected to a critical survey in conjunction with experiments on the same subject. In the following this paper is referred to as (J. K.). See also reference (9) page 28.

[2] The experiments for the separation of the uranium isotopes must also be mentioned on account of their great importance for the study of the fission processes despite the fact that the mass-spectrographs used are capable of working only with currents considerably smaller than those used in the above-mentioned experiments (2, 6, 7, 15, 16).

trographs. For instance, ion-optical systems are used instead of narrow slits for the collimation of the ions.

As there was strong reason to assume that a limit for the methods of mass-spectrographic separation of isotopes was far from being reached, a number of experiments has in recent years been carried out at the Institute of Theoretical Physics (J. K.). More particularly experiments have been made on the application of the Lamar, Samson, and Compton ion source (12), which in advance must be considered especially suitable for this purpose. It was found that by means of this ion source

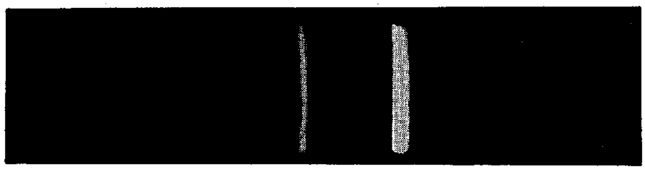

Fig. 1. Mass-spectrum of boron.

and a suitable system of electrostatic lenses using high voltages, it was possible to produce ion beams of exceptional homogeneity. A mass-spectrographic analysis of the ion beam undertaken preliminarily with a magnet of small resolving power ($\Delta m/m \approx 1/50$) further proved that by adding to the ion source various gases or vapours of chemical compounds it was possible to produce large quantities of atomic ions. By adding borontrifluoride it was thus possible to produce intensive beams of atomic boron ions. A specimen mass-spectrum is shown in Fig. 1. In this case boron ions with an energy of 43 kev impinge on a fluorescent screen and the light emitted is photographed from the opposite side. It further proved that C^+-ions might be produced from CO_2, CCl_4 and CS_2. The last-mentioned compound was used also for the production of S^+-ions. Ions of chlorine were produced from both CCl_4 and $TiCl_4$. By adding bromium vapour mixed with a small quantity of argon, ions of atomic bromium were produced. The atomic ion currents, measured by means of a Faraday cylinder which did not allow secondary electrons to escape, ranged between 1 and 10 μa.

With a view to continued experiments a large electromagnet has now been erected in the Institute, whereby the resolving power of the mass-spectrograph has been increased to more than 1:238, according to the acceleration voltage and the ion current used. By this construction a basis has been created for further experiments on the effective separation of isotopes, it being now possible to extend the experiments to even the heaviest elements. Experiments on the collection of separated isotopes have already been commenced.

The method developed for the production of beams containing a given species of ions with practically the same energy ($\Delta E/E < 3.5 \cdot 10^{-6}$) must further be considered especially suitable for a study of the interaction between ions and other atomic particles for primary energies from about 20 kev and upwards. In view of this versatility the following description of the mass-spectrograph may already at this stage be of interest.

The Resolving Power of a Homogeneous Magnetic Field.

The acceleration- and lens-system for the formation of the ion beam was developed empirically. In the planning of the construction of the magnet the following considerations of the course of the ion paths in a homogeneous magnetic field were used, the data of the ion beam (diameter d, energy spread ΔE, and the maximum angle α of the ion paths with the axis of the beam) being known approximately.

The ion beam is deflected 90° in the analyzing system of the mass-spectrograph. In what follows the resolving effect of the magnetic field will be calculated and a survey given of the main quantities determining the breadth of the lines (cf. 23 and (J. K.)). In this connection the effect of the magnetic stray field and space charges within the beam are left out of consideration. In order to make it easier to follow the course of the ions we may consider them emitted from a circular area of diameter d at the entrance to the magnetic field at any angle with the normal of the plane within the limit α and at energies within the interval $e\,(E \pm \frac{1}{2}\Delta E)$.

First, we shall consider the course of a beam of very small diameter ($d \to 0$) containing ions with absolutely parallel paths and of mass M and energy eE, entering the magnetic field H at P (Fig. 2 a). The ions will move in a circle with centre O and radius $r = H^{-1}\sqrt{2EM/e}$. Ions of mass $(M + \Delta M)$ will move in a somewhat larger circle and at P' we shall have a mass-dispersion of

$$\Delta r = r\left(\sqrt{1+\frac{\Delta M}{M}}-1\right) \approx \frac{r}{2}\cdot\frac{\Delta M}{M};\ \Delta M \ll M. \qquad [1]$$

If we introduce the mass-number A, we have

$$\Delta r \approx \frac{r}{2}\cdot\frac{\Delta A}{A}. \qquad [2]$$

In Fig. 3 Δr is plotted as a function of the mass-number A for $\Delta A = 1, 2, 3$, and 4 for the mean radius of curvature of the ion beam of $r = 80$ cm. as used in the experiments.

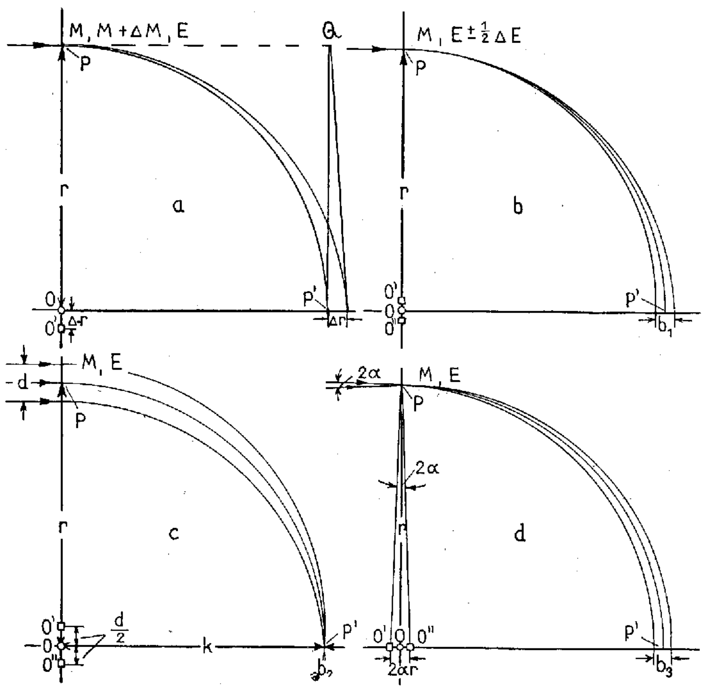

Fig. 2. Ion beams in a homogeneous magnetic field. Ions of mass M and energy eE moving on circles with radius r.

As appears from Fig. 2 a, the ions apparently emerge from a virtual source Q. If, therefore, we let the ions continue on their paths outside the magnetic field, we shall obtain a mass-dispersion between the two beams increasing proportionally with

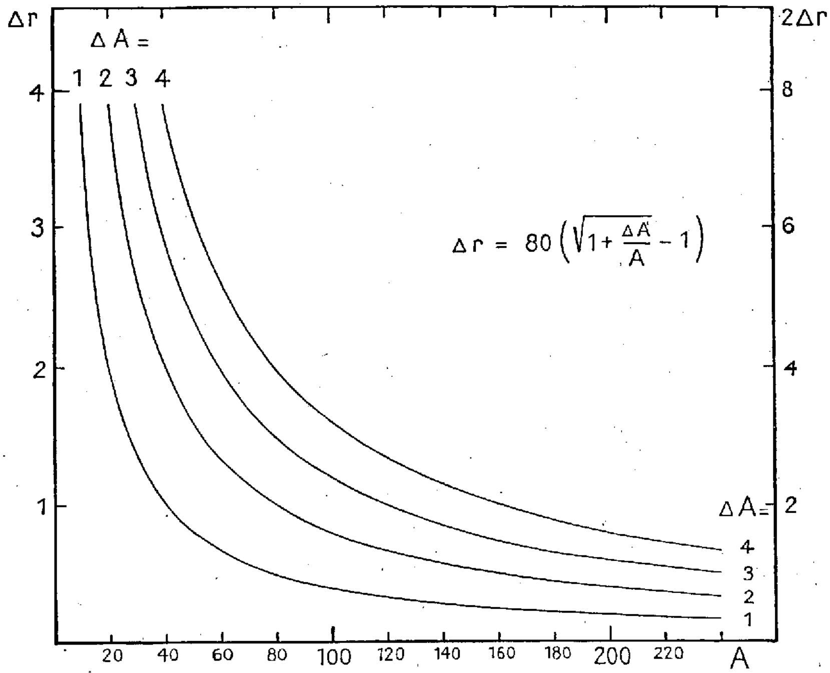

Fig. 3. The mass-dispersion Δr (in cm.) of an ion beam after deflection of 90° in a homogeneous magnetic field as a function of the mass-number A with ΔA as parameter ($r = 80$ cm.).

the distance from Q. In the present apparatus collecting cylinders and fluorescent screens are placed at a distance of $2r$ from Q and the mass-dispersion will thus be twice as large as at the exit from the magnetic field (cf. the ordinate on the right in Fig. 3).

As the most favourable place for collecting the ions depends on the ratio between the mass-dispersion and the breadth of the lines (the 'reduced mass-dispersion'), the course of the ions during the passage through the field must be further examined. The extent of the beam in the direction of the radius vector (r, Fig. 2) is called its breadth, the extent in the direction of the magnetic field force its height.

If the ions have an energy spread of $e\Delta E$ (Fig. 2 b), we shall consequently at P' have a breadth of the ion beam of

$$b_1 \approx \frac{r}{2} \cdot \frac{\Delta E}{E}; \quad \Delta E \ll E. \qquad [3]$$

(The ripple of the high voltage generator is considered small in relation to ΔE).

By means of Fig. 2c we shall now consider the course of an ion beam of diameter d. The ions are still assumed to have parallel paths at P ($\alpha \rightarrow 0$) and to have mass M and energy eE. At P' the beam is focussed as will be seen from the figure. The breadth of the beam at this place is

$$b_2 \approx \frac{d^2}{8r}; \quad \frac{d^2}{4r^2} \ll 1. \qquad [4]$$

Finally, we shall consider Fig. 2 d, showing ions being emitted from the point P at all angles within the limit α. The resultant breadth at P' is

$$b_3 \approx 2\alpha r; \quad \alpha \ll 1. \qquad [5]$$

In the direction of the magnetic field force the ions will not be affected, and the height of the beam at P' will therefore be $h = d + \pi \alpha r$.

We can now state the condition for ions of mass-numbers A and $(A + \Delta A)$ being separated at the exit from the magnetic field. The total breadth B of the lines must satisfy the condition

$$B = b_1 + b_2 + b_3 \leq \Delta r. \qquad [6]$$

According to these considerations the line breadth may be expected to increase when receding from P', which fact is especially apparent from Fig. 2. The question as to whether the reduced mass-dispersion will increase or decrease, however, may be settled only by consideration of an actual example in which the values b_1, b_2 and b_3 may be calculated. It will subsequently be shown that in the present experiments b_3 makes the largest contribution to the total breadth. In order to ascertain the exact course of the ion paths, regard must also be paid to the effect of the magnetic stray field. As already indicated especially favourable conditions were empirically found at the distance $2r$ from Q.

In the calculation of the line breadth the further simplification was made, that the effect of space charges on the course of the ion beam could be disregarded. An exact calculation of their influence is not quite simple, partly because of the focussing properties of the magnetic field and partly because of the fact that the beam is split up into several parts.[1] Hitherto we thus have only made use of the following simple considerations, which are based on results of WATSON (26, see also (J. K.)), in

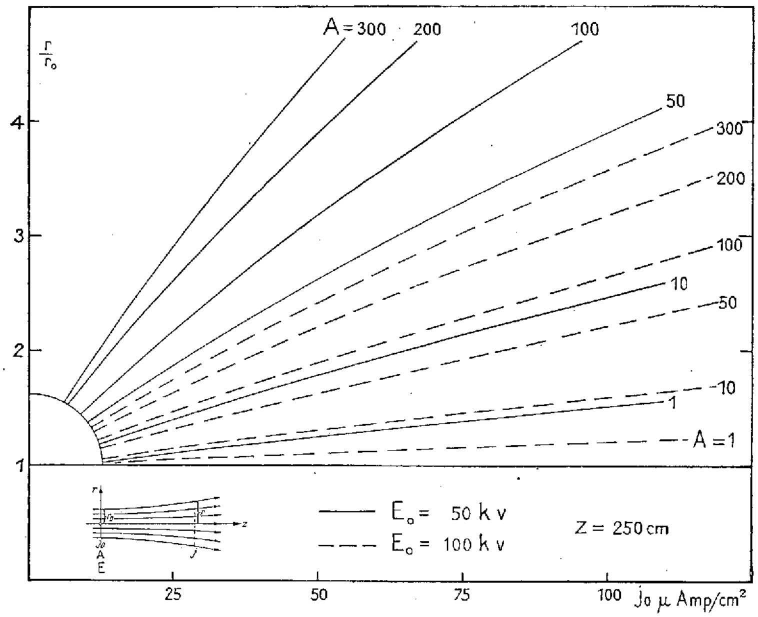

Fig. 4. Dispersion of ion beams on account of the mutual repulsion of the ions; $\left(\frac{r}{r_0}\right)$ as a function of j_0 for different values of A and E.

order to obtain a rough idea of the influence of space charges in the present experiments.

Let us consider a beam of parallel ions with the current density j_0 (cf. in what follows the drawing in the lower left corner of Fig. 4) passing at $z = 0$ through a circular aperture with radius r_0, moving thereafter into a field-free space. As a consequence of the mutual repulsion between the ions the beam will diverge and, having passed through a distance z, have

[1] Recently WALCHER (25) has investigated the influence of space charges on the focussing properties of a homogeneous field. These considerations must, however, be further extended in order to be utilised for the discussion of the present apparatus.

a somewhat greater radius r. Assuming that the ions have the same energy eE and mass-number A, we can calculate the divergence r/r_0 of the ion beam from the equation:

$$I\left(\frac{r}{r_0}\right) = 1.137 \cdot 10^{-2} \cdot \left(\frac{A \cdot j_0^2}{E^3}\right)^{1/4} \cdot z \approx \frac{r}{r_0}, \qquad [7]$$

when j_0 is given in $\mu a/\mathrm{cm}^2$, E in kv and z in cm.[1]

In Fig. 4 r/r_0 is plotted as a function of the current density j_0 within the interval of special interest with A and E as parameters. The value of z used corresponds to the distance passed by the ion beam in the mass-spectrograph later described from the centre of the electrostatic lens until it hits the fluorescent screen. If the current density is e. g. $j_0 = 50\,\mu a$ at an acceleration voltage of $E = 50$ kv, as generally used in the experiments, we may expect a considerable divergence of the ion beam in the case of heavy ions. Notwithstanding that a higher acceleration voltage of e. g. 100 kv will reduce the space charge effect somewhat, there can be no doubt that this effect will impose a practical limit on the mass-spectrographic separation of isotopes even if it might be possible to construct ion sources with higher yields of atomic ions than known hitherto.

In order to make it possible to work later on with higher voltages than 50 kv (the preliminary operating voltage of the electrostatic lens) at which space charge effects are reduced, the magnet of the mass-spectrograph was dimensioned so as to deflect uranium ions of an energy as high as 80 kev; for lighter ions the energy used may be correspondingly higher.

Design of the Mass-Spectrograph.

The mass-spectrograph is shown in cross-section in Fig. 5. The ion source and the lens system are placed on top of a casing with openings to the high vacuum pumps and mounted on the massive magnet. By means of a strong electric field the

[1] In the interval $1.3 < I < 5$ we have $I \approx r/r_0$ with an accuracy of less than 10 per cent. The correct expression on which the curves in Fig. 4 are based, is

$$I\left(\frac{r}{r_0}\right) = \int_1^{\frac{r}{r_0}} \frac{d\left(\frac{r}{r_0}\right)}{\sqrt{\ln\left(\frac{r}{r_0}\right)}}. \qquad [8]$$

ions are drawn from the plasma of the arc, and by passing through the tubular lens consisting of three cylinders a beam of ions with almost parallel paths is formed. When the ions have passed through the casing they enter the magnetic field, where they are deflected 90°. Finally, the beam proceeds some way outside the magnet until the ions hit the collecting cylinders or the fluorescent screen.

The ion source is a low voltage arc built on the Lamar, Samson, and Compton principle (9, 12, 14).[1] The length and diameter of the capillary are 10 mm. and 4 mm., respectively, and the aperture in the side of the capillary through which the ions are emitted has a diameter of ab. 1 mm. The anode and the cathode holders, which carry an 0.7 mm. tungsten filament, are water-cooled. The gas supply from two glass containers is regulated by means of two valves provided with vacuum-tight bellows. The gas pressure in the ion source must be $0.6 \cdot 10^{-2}$—$6 \cdot 10^{-2}$ mm. Hg. The arc current as a rule was less than 1 ampere at an arc voltage of 50—60 volts. The energy for operating the ion source which is connected with the high voltage generator is delivered from a belt-driven power stack and from a cathode current transformer insulated for 60 kv.

The electrostatic lens consists of three brass cylinders. According to earlier experiments sufficiently good conditions could be obtained with a fairly simple arrangement (10). In order to obviate aberrations of the lens, the diameter of the cylinders was made a great deal larger than that of the ion beam. The cylinders D_1 and D_3 are earthed, whereas the middle one has a "lens-potential" of about two-thirds of the acceleration potential (retardation lens).

The lens potential is derived from a high voltage potentiometer of 67 $M\Omega$ (Siemens resistances type 4 a) immersed in oil. By interposing a further, variable resistance of up to 20 $M\Omega$ on the earthed side of the potentiometer a precision adjustment of the lens-potential for focussing the ion beam may be obtained. The different parts of the lens were aligned by rule of thumb, no later changes being possible, whereas an adjustment of the ion source in relation to the lens might be made during the

[1] The ion source has been constructed by J. M. Lyshede, M. Sc., of the Physical Institute of the University of Aarhus, and has kindly been put at our disposal.

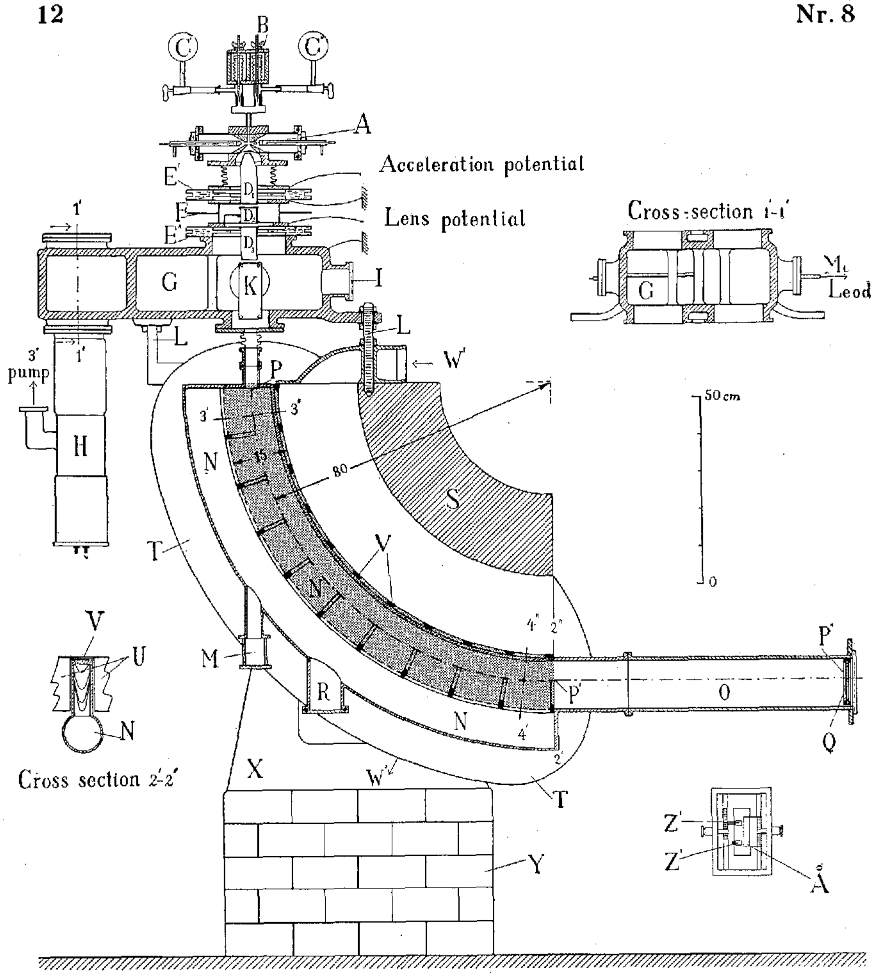

Fig. 5. Drawing of the mass-spectrograph. *A*: ion source. *B*: valves for control of gas from the containers *C′*, *C″*. D_1, D_2 and D_3: elements of the tubular electrostatic lens, isolated from each other by plates of glass *E′*, *E″* and a glass cylinder with a Pertinax screen *F*. *G*: casing on which the ion source and the diffusion pumps *H* are mounted. *I*: glass window for observation of the ion beam. *K*: plate condenser for deflection of the beam at right angles to the plane of the paper. *L*: stay-bolts with threads for adjustment of the lens system in relation to the magnetic field. The undeflected ion beam can be observed in the glass cylinder *M*. *N*: analyzing chamber with extension *O*, on which the fluorescent screen *Q* (or the Faraday cylinders) is (are) placed. *R*: connection for diffusion pump. *S*: yoke of the magnet. *T*: guard screens for protection of the magnet coils. Between the pole pieces *U* a number of distance pieces, *V*, are inserted. *W′* and *W″*: Air admission and air exhaust, respectively. *X*: iron base of magnet resting on concrete pillars *Y*. In the lower right corner is shown the arrangement for measurements with the moveable Faraday cylinders *Z′*, *Z″* in connection with observation of the beam on the fluorescent screen *Å*, to which the beam can be bent by the plate condenser *K*.

experiments by interposing another large vacuum-tight bellows. Glass plates and a glass cylinder with a pertinax shield to prevent surface discharges were used as insulators.

The oil diffusion pumps are mounted on the casing as close to the ion source as possible (cf. the drawing of cross-section $1'-1''$). The pump system consists of two 5″ pumps in parallel, backed by a 3″ and a 2″ pump of the type ordinarily used in the Institute (1). To produce the forevacuum a Pfeiffer mechanical pump Type 30100 was used. During the experiments the pressure measured by both a McLeod manometer and a Pirani manometer amounted to less than 10^{-5} mm. Hg.

The analyzing chamber is also connected with the casing by a bellows. As the latter is mounted on the magnet by means of threaded stay-bolts, the whole upper part of the apparatus may easily be adjusted so that the ion beam may be correctly aligned against the magnetic field.

The analyzing chamber consists of a flat, circular box to the outside of which a wide tube is attached (cf. the drawing of cross-section $2'-2''$). This arrangement was made to facilitate the removal of the gases given off by the metal walls. In order to keep the gas pressure extremely low, the chamber is provided with a flange for connection of a 5″ diffusion pump, but so far this arrangement has not been used. On the analyzing chamber in continuation of the axis of the lens a glass cylinder is placed for observation and adjustment of the undeflected ion beam.

Outside the magnetic field the analyzing chamber extends into a flat box provided at the end with a large flange, on which Faraday cylinders and fluorescent screens are mounted. The fluorescent screens are made of glass coated with a thin layer of fluorescent material (mainly ZnS), and in order to avoid electrical charges on the screen preventing the ion beam from remaining stationary, thin molybdenum wires are drawn across the surface of the glass at intervals of 4 mm.

When ion currents are measured by means of the Faraday cylinders it is convenient to be able to check the form and position of the lines of the mass-spectrum on a fluorescent screen without the nesessity of changing the magnetic field. A fluorescent screen was therefore mounted next to the Faraday-cylinders as will be seen in the lower right corner of Fig. 5. In order to give the ion beam the necessary deflection in direction of the magnetic field force a plate condenser (length of plates 17 cm., spacing 2,5 cm.) was interposed just below the electrostatic lens. The required deflection voltage amounted to a few hundred volts only.

The magnet producing the magnetic deflection field is also partly shown in cross-section in Fig. 5. The pole pieces whose shape correspond to the stippled area in the drawing have a mean radius of curvature of 80 cm., a width of 15 cm. and are spaced 6 cm. apart. The cores on which the two magnetizing coils are mounted are not carried all the way to the ends of the pole pieces at P and P', but only cover a sector of 76° corresponding to the area within the two dotted lines $3'-3''$ and $4'-4''$. The coils consist of 50 layers containing 11 windings each of 3×7 mm. copper ribbon. The windings are continued right up to the pole faces in order to decrease stray fields.

The coils are encased in guard screens indicated in Fig. 5. The magnetic circuit is closed by a heavy yoke also partly shown in cross-section in the figure. To prevent reduction in the space between the pole-pieces by a bending of the yoke due to attraction between the poles of the magnet a series of distance-pieces have been interposed between them. The energy consumption in the coils at maximum current amounts to about 4400 watts. In order to keep the temperature at a suitable level when working for a considerable length of time, ventilation must be provided by means of a forge bellows capable of delivering up to 12 m^3 per minute. The temperature of the air then will rise by about 20° when passing through the magnet. The whole apparatus, which weighs about 4500 kg., is mounted on two concrete pillars. This arrangement facilitates access to the various parts and observation of the mass-spectra. The maximum field force that may be produced is about 8000 Ørsted, enabling uranium ions of an energy of 80 kev to be deflected.

As the magnetic field force is almost of the same value for increasing and decreasing values of the magnetizing current, it is easy to identify a definite ion species. The current for the magnet is supplied by a dynamo, the magnetizing current of which is controlled from the operator's post.

The magnetic field is exceedingly homogeneous near the middle of the centre line. In order that good results may be obtained the most essential point is, that the field force is kept constant within each cross-section at right angles to the direction of the beam. A smaller variation along the path of the beam

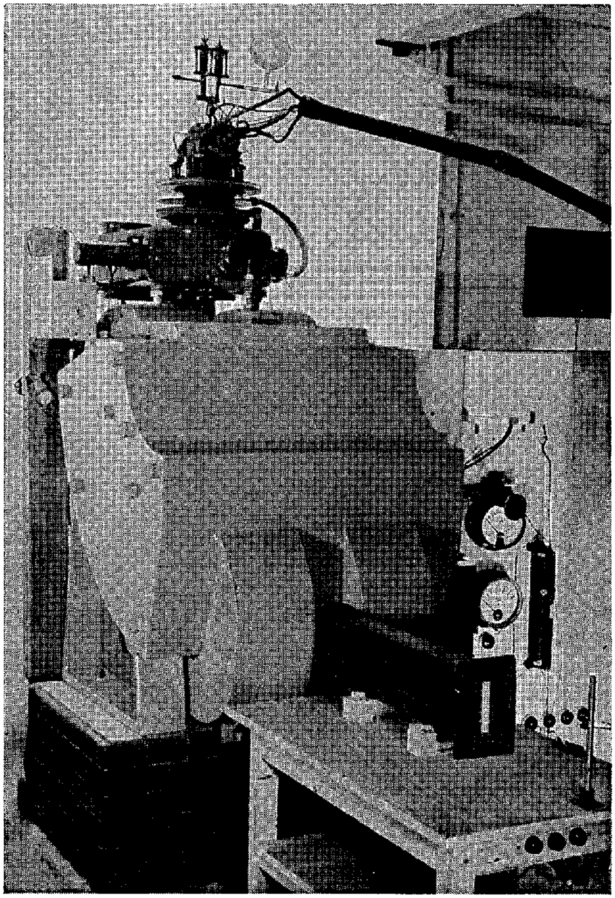

Fig. 6. Photograph of mass-spectrograph.

is of less importance. Measurements have shown that the magnetic field within the space passed by the ion beam deviates less than 1 per 1000 from the maximum field force in the centre line. Deviations of about 1 per cent. are found only at a distance of 3—4 cm. from the centre line. No further measurements of the field force have been made, as the preliminary measurements yielded satisfactory results and the most important information concerning the properties of the field was obviously to be obtained through experiments with the ion beam, which is exposed to the full effect of the field during its passage through the magnet.

The voltage for accelerating the ions was produced by an ordinary Greinacher generator with two rectifiers. In order to reduce the ripple sufficiently a filter consisting of resistances and condensers was interposed. The constancy thereby obtained was so great that the influence of the ripple on the breadth of the lines ($\sim 10^{-2}$ cm.) might be disregarded. The high voltage was measured on a micro-ammeter combined with a 50 cm. long resistance of 400 $M\Omega$. (Vitrohm resistances) immersed in oil. A photograph of the mass-spectrograph is shown in Fig. 6.

Experimental Results.

As the focussing of the ion beam was of decisive importance for the computation of the resolving power of the mass-spectrograph, the properties of the electrostatic lens system had been subjected to previous investigation (J. K.). In these experiments the fact was utilized that the ion beam at the prevailing current densities and gas pressures could be observed as a faintly luminous stripe. For the purpose of comparing the focussing of the lens at varying conditions a series of photographs of the beam was taken.[1] An example of such a photograph of the ion beam is shown in Fig. 7. In this photograph the fluorescent light from the glass around the electrostatic lens is seen at the extreme top, further down the ion beam can first be observed through a small window in the casing bearing the lens system, and subsequently its path may be followed over a considerable length in a glass tube the wall of which is covered with metal netting in order to obviate electrical surface charges. At the bottom of this tube a Faraday cylinder was placed for measuring the ion current. In the present experiment the acceleration potential was

[1] In a brief note in the *Physical Review* BUECHNER and LAMAR (3) state that they have independently photographed ion beams in highly evacuated tubes for the purpose of studying the focussing with ion lenses. According to the *Physikalische Berichte* (22, 2462 (1941)) a detailed treatise on this work has been published in an American periodical (4). We have not, however, been able to provide a copy.

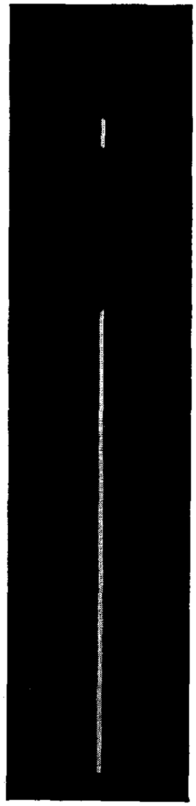

Fig. 7. Photographic record of the focussing of the ion beam. From the middle of the electrostatic lens at the very top of the apparatus and until it disappears into the Faraday cylinder at the bottom the beam passes through a length of ab. 117 cm. Measurement of the original negative shows that the diameter of the beam is about 1 cm. The records were taken with a *Leica* camera with *Summitar* objective. Exposure 10 minutes with diaphragm 2 and *Superpan* film.

45.5 kv and the ion current 30.8 μa (with an arc current of the ion source of 0.37 amp.), corresponding to the adjustment used for the recording of the mass-spectra. Hydrogen was added to the ion source and the mass-spectrographic analysis subsequently showed that in this case the ion beam mainly consisted of H_2^+ ions, whereas protons and H_3^+ ions were present in somewhat smaller quantities.[1]

As will be seen, the focussing was good, no divergence of the ion beam being observable. In conformity with the curves in Fig. 4 no appreciable divergence of the beam by space charges was to be expected under the prevailing conditions. In the case of stronger currents or heavier ions such an effect, however, could be observed.

In the first mass-spectrographic experiments with the large magnet, the fluorescent screen was placed at the exit from the magnetic field (at P' in Fig. 2 and Fig. 5). Experiments with several screens at increasing distances from the end of the pole pieces, which alternately might be turned into the path of the beam, however, soon showed that the reduced mass-dispersion increased with the distance from the virtual source Q of the beams (cf. Fig. 2 *a*). At distance $2r$ (P'' in Fig. 5) it was of sufficient magnitude to enable the experiments to be extended to include even the heaviest elements. This does not, however, prove that still better results cannot be obtained at greater distances under suitable focussing conditions.

[1] Further, on account of impurities, very small quantities of the following ions were found: O^+, $(H_2O)^+$, $(H_3O)^+$, $(CO)^+$, $(COH)^+$, and $(CO_2)^+$.

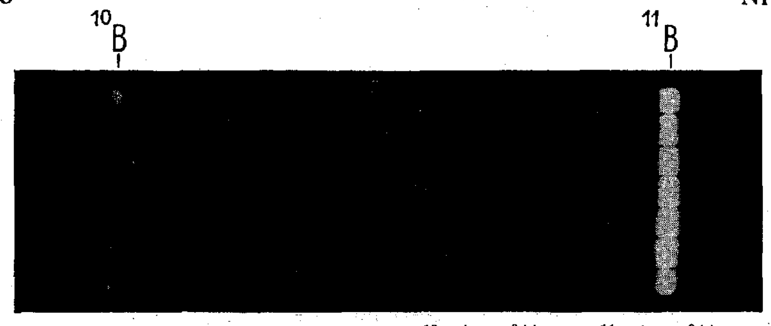

Fig. 8. Mass-spectrum of boron. Isotopes: ^{10}B (20.6 %) and ^{11}B (79.4 %). Photograph of the light from the fluorescent screen. *Leica* camera with *Summitar* objective and *Isopan-Ultra* film. Exposure: ab. 10 sec. Natural size. During the exposure the ion source was supplied with borontrifluoride.

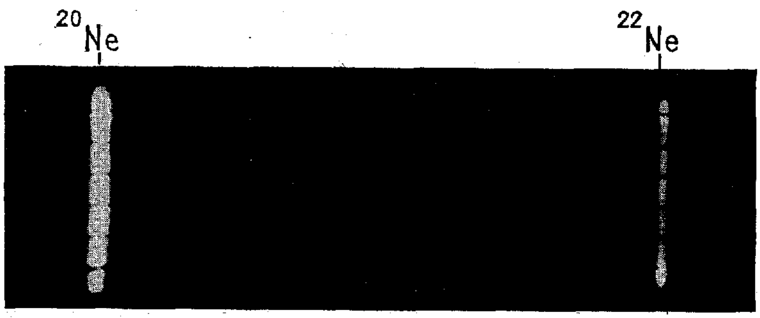

Fig. 9. Mass-spectrum of neon. Isotopes: ^{20}Ne (90.00 %), ^{21}Ne (0.27 %), and ^{22}Ne (9.73 %).

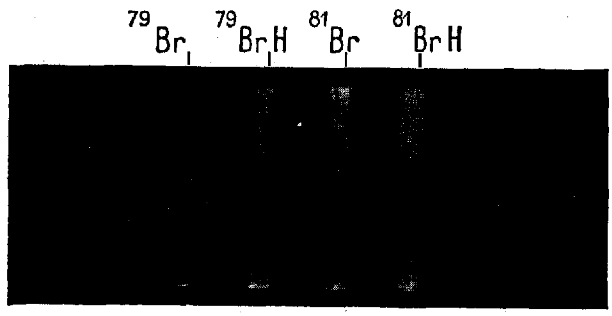

Fig. 10. Mass-spectrum of bromium. Isotopes: ^{79}Br (50.7 %), and ^{81}Br (49.3 %).

In order to demonstrate the resolving power of the mass-spectrograph the mass-spectra of various elements have been photographed. Figs. 8—12 show as typical examples the spectra of boron, neon, bromium, krypton and xenon. At these record-

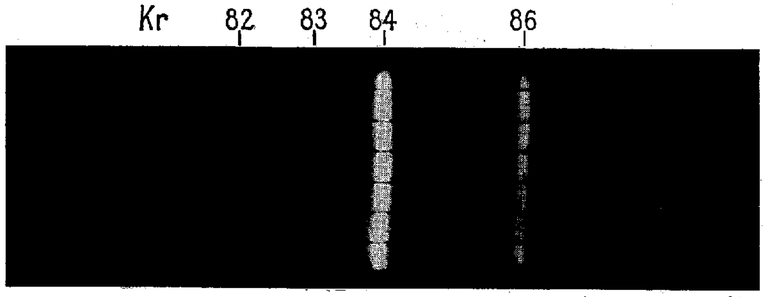

Fig. 11. Mass-spectrum of krypton. Isotopes: ^{78}Kr (0.42 %), ^{80}Kr (2.45 %), ^{82}Kr (11.79 %), ^{83}Kr (11.79 %), ^{84}Kr (56.85 %), and ^{86}Kr (16.70 %).

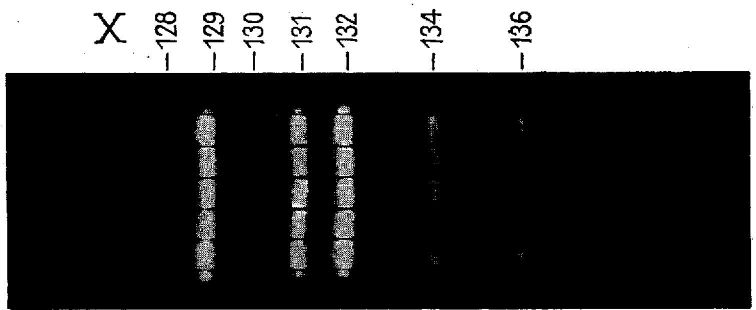

Fig. 12. Mass-spectrum of xenon. Isotopes: ^{124}X (0.08 %), ^{126}X (0.08 %), ^{128}X (2.30 %), ^{129}X (27.13 %), ^{130}X (4.18 %), ^{131}X (20.67 %), ^{132}X (26.45 %), ^{134}X (10.31 %), and ^{136}X (8.79 %).

ings the acceleration voltage was about 50 kv, the arc current ab. 0.3 amp., and the ion currents between 1 and 10 μa. The somewhat different luminosity within the individual lines is due to the irregular thickness of the fluorescent coating. The black stripes across the lines originate from the molybdenum wires stretched across the surface of the glass in order to remove electrical charges.

The boron spectrum shows the two boron isotopes ^{10}B and ^{11}B at a distance of about 72 mm. The luminosity of the lines approximately indicates the ratio between their abundance of ab. 1 : 4. Such an estimate, however, may be very deceptive if the ions hit a charred piece of the screen. The photograph shows that beams hitting the screen even at a considerable distance from the centre line (Point P'' in Fig. 5) are satisfactorily focussed.

In the following table the mass-dispersion measured is compared with the values computed according to [2]. No correction

Table of comparisons between measured and calculated values of the mass-dispersion of the mass-spectrograph.

Isotopes	$2\Delta r$ (meas.)	$2\Delta r$ (calc.)
$^{10}B - {}^{11}B$	72	80
$^{20}Ne - {}^{22}Ne$	74	80
$^{79}Br - {}^{81}Br$	20	20,3
$^{82}Kr - {}^{86}Kr$	37	39
$^{129}X - {}^{136}X$	41,5	43,4

has been applied for the fact that the light isotope does not impinge on the fluorescent screen at P'', as assumed in the calculations. It will be noticed that the mass-dispersion of $^{10}B - {}^{11}B$ is somewhat smaller than the calculated value. This must be due to the fact that the magnetic field diminishes at the ends of the pole pieces.

The measurement of the mass-spectrum of neon also shows a mass-dispersion somewhat smaller than that calculated. The weak isotope ^{21}Ne cannot be observed on the fluorescent screen. Besides the two equally frequent isotopes ^{79}Br and ^{81}Br, the mass-spectrum of bromium shows the presence of the respective hydrides. Such hydride formation would make it impossible to separate isotopes only one mass-unit apart. The possibility, however, exists that the hydrogen may be removed from the ion source by connecting the latter direct to a powerful pumping system, at the same time admitting large quantities of the gas the ions of which it is desired to produce, in order to maintain the necessary pressure to keep the arc burning.

The mass-spectrum of krypton shows only the four most frequent isotopes; thus, ^{78}Kr and ^{80}Kr could not be observed. The mass-spectrum of xenon shows seven of the nine known isotopes; ^{128}X, however, can only just be discerned. In this experiment the resolving power of the mass-spectrograph is obviously higher than $\Delta A/A = 1/238$. At weaker currents or higher acceleration voltage than in this case, both the breadth and height of the lines, however, will decrease and the resolving power will therefore increase still more. If the above data are reversed the resolving power will be decreased. This must, no doubt, be attributed to the mutual repulsion of the ions; for according to Fig. 4 we have here conditions in which this space charge effect becomes important on account of the heavy ions. For experiments of long duration the lens would not be able to stand acceleration potentials much higher than 50 kv, but

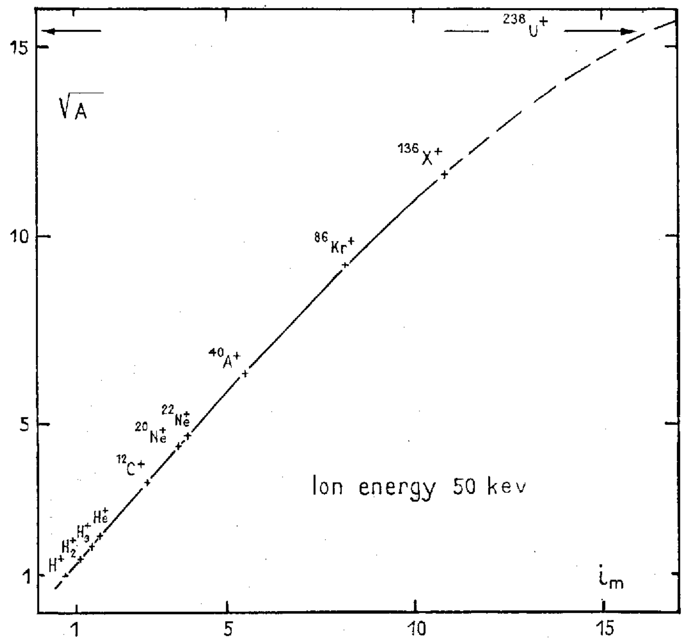

Fig. 13. Curve of adjustment taken with an acceleration voltage of 50 kv.

probably it will not be difficult to build a system which may be used for much higher voltages.

If we plot $\sqrt{A}$ as a function of that magnetizing current i_m which will deflect the ions sufficiently to hit the point P'' on the fluorescent screen (cf. Fig. 5), we shall obtain an adjustment curve as shown in Fig. 13 for an acceleration potential of 50 kv. This curve is extremely useful as a preliminary indication of the region within which a definite ion species may be found. Generally, there will be no doubt as to the identification of the lines, the mass-spectra often being very characteristic and, furthermore, only on rare occasions other ions will be found in the immediate proximity of those wanted.

We shall now show that from a measurement of the line breadths at the exit from the magnetic field, which in the case of medium ion currents and an acceleration voltage of 50 kv was ab. 0.3 cm., it is possible to derive important information as to the paths of the ions in the beam and also as to their mean energy when emitted from the ion source.

According to [3], [4], [5], and [6], the line breadth may be expressed as follows:

$$B \approx \frac{d^2}{8\,r} + \frac{r}{2} \cdot \frac{\Delta E}{E} + 2\,r\,\alpha. \qquad [9]$$

As the diameter of the ion beam at the entrance to the magnetic field according to the photograph (Fig. 7) is only 1 cm., we may disregard the contribution of the first term inasmuch as

$$\frac{d^2}{8\,r} \approx \frac{1}{8 \cdot 80} = 1.56 \cdot 10^{-3}\ \text{cm}. \qquad [10]$$

Already from the previous focussing experiments (J. K.) it was possible to conclude that the ions are emitted from the source at very small energies (< 1.6 ev). In what follows we shall try to determine this energy more accurately, and it is therefore presumed that the ions participating in the formation of the beam are emitted from the plasma of the arc with a Maxwell distribution or a similar energy distribution the energy spread $e\Delta E$ of which is of the same order as the mean energy $e\varepsilon$. Further, we make use of the well-known result (23) that on having passed through an electrostatic lens ions of energy eE will in the most favourable case move along paths the angle of which with the axis of the beam is

$$\alpha < \sqrt{\frac{\varepsilon}{E}}. \qquad [11]$$

On these assumptions the term [9] may be given in the following form

$$B \approx \frac{r}{2}\,\alpha^2 + 2\,r\,\alpha. \qquad [12]$$

As, however, $\alpha \ll 1$, we have

$$B \approx 2\,r\,\alpha. \qquad [13]$$

By introducing the numerical values we obtain:

$$\alpha \approx \frac{0.3}{2 \cdot 80} = 1.88 \cdot 10^{-3}. \qquad [14]$$

In other words, the maximum angle of the ion paths with the axis of the beam at the entrance to the magnetic field will be about 0.1°. A further, appreciable diminution of α and thereby of the line breadth B will for technical reasons be difficult, as in that case, in conformity with [11], we should have to use very high acceleration voltages.

From [11] and [14] we may compute the mean energy of the ions at departure from the ion source. It will be

$$e\varepsilon = e\alpha^2 E = e 3.53 \cdot 10^{-6} \cdot 5 \cdot 10^4 = 0.176 \text{ ev}. \qquad [15]$$

This means that the ions are emitted with initial energies approximately corresponding to the ion temperature in the arc (0.1 ev $\approx$ 900° K). The process of emission must therefore be assumed to take place in such a way that the ions are drawn straight from the plasma of the arc without subsequently colliding with other atoms, as such collisions would impart to the ions considerable velocity components at right angles to the direction of the beam, which would prevent focussing.

In view of these considerations, the Lamar, Samson, and Compton ion source is seen to be especially suitable for the present investigations. Hence, in designing other types of ion sources for similar purposes, it would obviously be reasonable to choose an experimental arrangement so that discharge and emission conditions approach those obtained in these experiments.

In conclusion it may be pointed out, that low voltage arcs provided with a probe to draw the ions out of the arc must be considered unsuitable for the present investigations, the ions being exposed to collisions in the canal of the probe with a consequent loss of energy. Yates (27) has used this form of ion source for the separation of the boron isotopes, but the mentioned influence of the probe on the emission conditions appeared very plainly from the fact that the mass-spectrum was not completely dissolved.

The high intensity mass-spectrograph described in what precedes will in the near future be used for experiments on the separation of isotopes in such quantities, it is to be expected, as to enable experiments to be made on pure samples. The apparatus for collecting isotopes is already finished. Certain difficulties will, no doubt, be encountered, such as e. g. impurities from the gases present in the apparatus. It has been found, however, that the oil diffusion pumps are capable of maintaining sufficiently low pressures with any of the gases hitherto used. By suitable placing of metal surfaces cooled by means of liquid air it may be possible entirely to prevent impurities from entering the collecting cylinders.

Other Applications.

On account of the great homogeneity of the ion beams obtained, both in respect of mass and energy ($\Delta E/E \approx 3.5 \cdot 10^{-6}$), the mass-spectrograph described may be used for a number of experiments for which the means have hitherto been lacking.

In the first instance the most obvious experiment would be the simple one of determining the yield of secondary electrons from metallic surfaces by bombardment with various ions with primary energies from about 20 kev and upwards. Preliminary experiments on these lines have already been carried out (J. K.) and inter alia, showed, extraordinarily high yields ($i^-/i^+ \backsim 20$) for certain molecular ions. By observing the fluorescent light from glass or from the substances covering its surface, it was further found that the colour of the light depended upon the ion species and the nature of the screens. Thus, the light from a glass screen when bombarded with H^+- and A^+-ions was blue and red, respectively. However, so far these experiments have not been continued.

It must, further, be possible to investigate the interaction between high velocity ions and atoms by letting the ions pass through a canal into a chamber with higher pressure than that of the analyzing chamber. It would be of importance for certain astro-physical calculations to obtain approximate values of the cross-sections between high velocity ions and free atoms, even if the energies considered in these calculations are not so high as those here contemplated.

By using a lens system similar to the Institute's large high voltage tube for nuclear research (1) it will be possible to extend such investigations to comprise experiments with ions of greater energies than those considered in the present paper. In the case of heavy ions the magnetic field of the mass-spectrograph, however, will soon become too weak. In that event it will be possible to accelerate the ions after their passage through the mass-spectrograph and for this purpose either of two principles may be applied. One alternative is to use a constant acceleration potential which, however, entails the drawback that the apparatus for the investigation of the effects of the ions will attain a high, negative potential. The second alternative is the application of alternating electric fields as used by LAWRENCE and SLOAN (13) in the construction of their linear accelerator. By applying this principle we obtain the result that the ions which leave the earthed analyzing chamber with an energy corresponding to the acceleration potential will be further accelerated by the alternating fields and then will impinge on the likewise earthed target.

Summary.

The question of mass-spectrographic separation of isotopes has been discussed by several authors from many different points of view. A critical survey of previous investigations in connection with a series of experiments made in recent years at the Institute of Theoretical Physics has shown that hitherto the possibilities of separating isotopes by mass-spectrographic methods have not been fully exploited (9).

This paper describes a mass-spectrograph constructed on the basis of the experiments mentioned above and having a resolving power of more than $\Delta A/A = 1/238$ at an ion current of 10 μa and an acceleration potential of 50 kv. Experiments on the separation of isotopes may thus be extended even to the heaviest elements. The ion source used was a low voltage arc of the Lamar, Samson, and Compton type, as by means of this apparatus it is possible to produce beams of atomic ions of

probably all elements added to the arc in the gaseous state or in the form of vapours of chemical compounds.

For the focussing of the ion beam a simple tubular lens (retardation lens) was used. The dispersion of the beam was made by means of a homogeneous magnetic field, the mean radius of the path of the deflected ions being 80 cm. The maximum field force of the magnet for continuous operation is about 8000 Ørsted, which is enough to deflect uranium ions of an energy of 80 kev.

In a separate chapter the mass-dispersion of the mass-spectrograph and the breadth of the lines of the mass-spectrum at the exit from the magnetic field are calculated. An especially high resolving power was found experimentally at a distance of 80 cm. from the ends of the pole pieces. An attempt was made at estimating the disturbing influence of electrical space charges. In a later chapter a detailed technical description of the mass-spectrograph is given. To maintain a sufficient vacuum oil diffusion pumps were used capable of pumping all substances so far used in the experiments.

Photographs of the ion beam, which might be observed as a slightly luminous stripe in the evacuated space, show the focussing properties of the electrostatic lens. As examples of the resolving power of the mass-spectrograph, mass-spectra of boron, neon, bromium, krypton, and xenon are shown by photographs of the light from a glass screen coated with a fluorescent substance. The measured values of the mass-dispersion are somewhat smaller than the calculated values as the magnetic field diminishes towards the ends of the pole pieces.

From the breadth of the lines at the exit from the magnetic field it is in the first place possible to determine the maximum angle of the ions to the axis of the beam at the entrance to the magnetic field, which angle appears to be about 0.1°. Next, the mean initial energy of the ions when emitted from the ion source may be calculated at less than 0.2 ev, that is to say that the ions are emitted from the arc with energies nearly corresponding to the ion temperature in its plasma.

The mass-spectrograph described is in the first instance to be used for experiments on the separation of isotopes already commenced. Attention is, however, called to the fact that this device seems well suited for a number of other experiments, such as e. g. investigations on the interaction between high velocity ions and other atomic particles.

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