A High Intensity Mass-Spectrometer

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A mass-spectrometer has been constructed in which is used a new type of magnetic lens capable of focussing on a slit all the positive ions of a given mass from an extended source. Electrostatic focussing permits 12 percent or more of the ions from an area of 30 sq. cm to be brought into a nearly plane beam and focussed by the lens. Practically complete separation of the potassium isotopes has been accomplished with an ion current of 0.1 milliampere for K^{39}, which deposits one milligram in seven hours. Samples of Li^6 and Li^7 have been collected.

SINCE the discovery in 1919 of isotopes of non-radioactive elements, many attempts have been made to obtain pure specimens of individual isotopes in large enough amounts for experimental purposes, with no success except in the case of hydrogen and those gases to which the Hertz diffusion process may be applied. The method of Hertz is suitable only for the separation of the lightest and heaviest isotopes of a group which can be obtained in gaseous form and to isolate any member of a group it is necessary to use some form of mass-spectrometer. Although the quantities yielded by this method have formerly been hopelessly small, it is evident that if all positive ions emitted from a large area could be concentrated on a slit and simultaneously sorted as to mass, the problem, for some elements, would be solved. About ten years ago the idea of using a magnetic lens for this purpose was suggested. The positive ions from an extended source were to be accelerated in an electric field to form an ion beam homogeneous in direction and velocity, which would then pass through a uniform magnetic field whose boundaries were so shaped that all particles of a certain mass would be focussed on a slit beyond the field.

In the first type of magnetic lens constructed, the equations of the boundaries of the magnetic field were $y=0$ and $x(r^2-y^2)^{\frac{1}{2}}=(c-y)y$ for the incident and emergent edges, respectively. The beam entered parallel to the Y axis, travelled in a circular arc of radius r in the field and came to a focus at the point $y=c$ on the Y axis. This lens functioned poorly for many reasons, among which were lack of homogeneity of the pole pieces and poor vacuum construction. The apparatus was worked intermittently for several years, however, with the object of bringing out defects which could be eliminated in a second lens.

Meanwhile, a very much simpler shape of the magnet pole-pieces was found (Fig. 1), in which both boundaries of the field are circles passing through the origin, one having its center at the focal point c and at the other at c', a distance r to the right of c, where r is the radius of curvature of trajectories in the field. This lens has a much sharper focus for masses falling above and below c than the first type had and is also simpler to

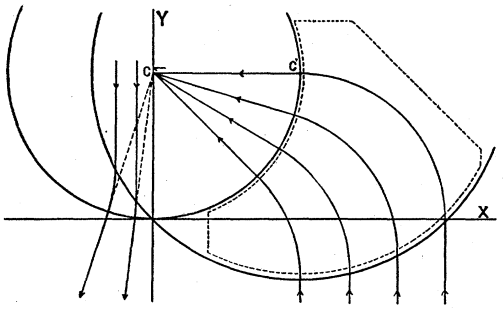

FIG. 1. Cylindrical magnetic lens formed by a uniform magnetic field with circular boundaries having centers at C and C'. Paths of positive rays, e.g., K^{39}, of proper voltage are shown converging to a focus at C from the right and diverging from a virtual focus C at the left. At the same voltage K^{41} comes to a focus at the point checked above C. The outline of the pole-piece used, which is corrected for edge effect, is dotted in.

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construct. It is interesting to note that if the circles are continued to the left of the Y axis we have a diverging lens with a virtual focus at c, as shown in Fig. 1. Construction of a mass-spectrometer around a lens of this type was begun by L.H.R. in 1931. Since, in actual practice, the field does not have the sharp boundaries hitherto postulated, it was considered advisable to compute the fields near the edges of the pole-pieces by a Schwarz transformation, plot the path of the particles through the field graphically, and determine the correction to be made. It resulted that, to a good approximation, both edges of the field remained circular, the convex edge of the pole-piece having its radius reduced from 28.735 cm to 28.100 cm and the concave radius being increased from 20.320 cm to 20.955 cm. The gap between the pole-pieces was 0.635 cm and the radius of the path in the field for focussing was 20.320 cm. The actual outline of the pole-pieces after correction is shown, dotted in, in Fig. 1, and in perspective in Fig. 2. The pole-pieces, marked AA in Fig. 2, are made from forgings of Armco Iron which were machined roughly, annealed, and then finished. They are 10 cm thick, separated by brass spacers, and held together by four brass bolts. When the air gap field is 2000 gauss, the variation over the central region is less than one gauss.

The Armco Iron side pieces BB, of 200 sq. cm section, are bolted to the pole-pieces and carry the studs CC by which the apparatus is supported. The magnet coil D, having 890 turns, surrounds a hollow Armco Iron box, E, in which the number of Armco Iron bars FF may be varied to produce saturation in this part of the circuit for the current used, thus minimizing magnetic field fluctuations. A rectangular box G, of half-inch brass, is screwed and soldered to the bottom of the pole-pieces and to the top of the brass cylinder H, of 20 cm internal diameter. On the open end of the latter is screwed and soldered a heavy flange, leaving the edge of the cylinder protruding. This edge is turned down to fit snugly into a narrow circular groove, containing a rubber gasket in the heavy circular end plate I, through which the water-cooling tubes pass. The water tubes for the source pass through an insulating cone fitted into a sylphon

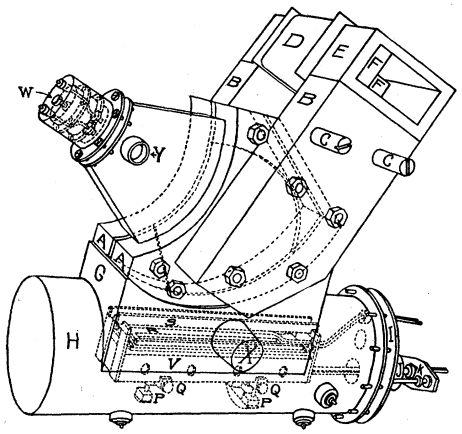

FIG. 2. Perspective drawing showing, in solid lines, exterior view of mass-spectrometer. The outline of the pole-piece is completed by dotted lines and the source assembly and the receiving arrangement is also dotted in.

tube J and supported outside by an insulated bridge K. The source assembly is supported on insulating blocks PP and can be adjusted in position laterally by the screws QQ and vertically by screwing the legs in or out.

The simple source arrangement in which the accelerating potential is applied between a plane rectangular emitting surface and a plate with a rectangular hole opposite the emitter is unsatisfactory. If the electrodes are put far enough apart to make the field essentially uniform, space charge makes the limit of emission very low. If grids are used in such a way as to reduce the effect of space charge, they scatter the beam badly, and the grid wires must be separately mounted to allow for thermal expansion. This source also restricts the useful emitting area to the cross section of the beam which can pass between the pole-pieces.

If space charge be neglected, however, it is possible to solve by a mechanical analogy this problem of concentrating the emission from a large area into a thin, flat beam of parallel trajectories. The deflections of a stretched elastic membrane obey a differential equation $\partial^2 V/\partial x^2 + \partial^2 V/\partial y^2 = 0$, which is identical with Laplace's equation for the electrical potential in two dimensions. A rubber membrane was stretched over a horizontal, plane frame, portions of the membrane were elevated with configurations and elevations corresponding to the shape and

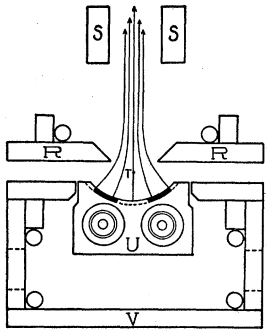

FIG. 3. Section of source assembly showing the heated block U, upon which the emitter is shown in black, and the water-jacket V surrounding it. The accelerating potential is applied between UV and the water-cooled slit R. Path of particles in absence of space charge shown by arrows. Evacuation holes are dotted at sides.

electric potentials, respectively, of a cross section of the source and neighboring conductors, and steel ball bearings were released at the boundary corresponding to the emitting surface so that their paths were those which ions would follow in the corresponding electric field. Deviations of the balls due to rolling friction, etc., were small, since varying the mass of a ball by a factor eight produced little change in its path. The design obtained from this analogy consisted of a portion of a circular cylinder completely covered with emitter, close above which was placed a bevelled slit (RR, Fig. 3). By adjusting the curvature of the emitting surface, the width and bevel of the slit, and the distance between slit and source, the emission from all parts of the surface can (in the absence of space charge) be concentrated into the narrow, parallel beam indicated in the figure. To eliminate the effect of slight errors in adjustment there is installed a pair of "focussing bars" SS, whose potentials may be adjusted to diverge or converge the beam or swing it to right or left.

Because the electric field intensity over the emitting surface is not uniform, it is evident that with large emission unequal space charges will build up and destroy the focussing. This upper current limit for focussing was found to be microamperes instead of milliamperes as we had hoped. S.S.W. has made many partially successful attempts to overcome this difficulty with wires and grids, the best of which arrangements we are now using. (Fig. 3.) In this design the emitting substance is put only in the places shown in black in the figure and has a total area of 30 sq. cm, and a wire T, whose potential is adjustable, has been installed. With this arrangement one can collect only about 12 percent of a total emission when this is as high as a milliampere. (We include in the total emission any electron current from the slit to the emitter, which may be quite considerable.) This is a workable amount, but it will undoubtedly be improved in the future.

As shown in Fig. 3, the source block U is machined from an iron bar with two large holes for heating elements. The globar heaters first used with this heated well, but were fragile and gave off a great deal of gas, due apparently to the "drying up" in the vacuum of the aluminum-filled iron cups which made contact with the ends and the development of an arc. When the globars were replaced with 35-mil molybdenum wires wound on 8 mm Stupekoff tubing, our heater troubles ended. At first some care was taken to eliminate the magnetic field of the 50 cycle heating current, but this has since proved almost unnecessary. To dissipate the 2000 watts radiated by the source, it is surrounded by a heavy water-jacketed copper box V at the same potential, and thinner copper shields (not shown) are extended up from the sides of the slit plate. The copper slit plate which is earthed to the case, is also water-cooled. All insulating supports are made from talc which has been fired after shaping. This source can attain 1450°K, at which temperature the iron evaporates noticeably, without permanent injury and so is suitable for several Kunsman catalyst alkali metal emitters. In order to get full space-charge-limited emission with lithium, the bar must be made of some more refractory material, perhaps graphite. The current for the heaters is supplied through an insulating transformer from the 110 volt mains, and the accelerating potential is furnished by a 6000 volt, 20 kw, d.c. generator, which is very steady. The accelerating and accessory voltages are obtained by a potentiometer arrangement which at present will only handle about 4000 volts but will be rebuilt to take 6000 volts. The current for the magnetic field, about 5 amperes for potassium when the

accelerating potential is 4000 volts, is obtained from storage batteries.

The receiving assembly is shown at the upper left of Fig. 2. The cylindrical box in which the slits are mounted can be moved in or out by the screw W, which is rendered vacuum-tight by running beeswax around the head. A one-millimeter slit is used for determining the point of best focus and for making other adjustments but is widened to include the whole peak when collecting samples. Double slits and double collectors enable both potassium isotopes to be collected simultaneously. When one is actually collecting, the slits are crossed by fine wires, and the potential of the cups is maintained a few hundred volts from that of the source. The retarding potential of several thousand volts between cup and slit prevents any secondary electrons from leaving the collector and falsifying the current measurement and also prevents energy dissipation at the collector and the knocking off of the deposit by the impacts of newly arriving particles. The insulating plug supporting each cup is a double cone, a metallic sheath about the inner cone shunting leakage current around the measuring instrument.

The apparatus is evacuated through the tube X, and a Pirani gauge attached to Y, indicates the pressure inside. If the vacuum is good, the chief factor limiting the resolving power is the component of the thermal velocity perpendicular to the accelerating field. The curve shown in Fig. 4 has a breadth closely corresponding to that to be expected if this is the only cause of divergence. This curve was run with a receiving slit one-half millimeter wide, a voltage V of 2350 volts, a source temperature T of 1100°K, and a pressure of 5×10^{-5} mm of mercury. This curve can be reproduced with the highest emission of which the apparatus is capable, provided that the ratio V/T, which governs the Maxwell distribution of thermal velocities, is kept constant, and the apparatus is suitably outgassed. The highest conveniently obtainable ion current to the collector is 0.1 milliampere, with the slit widened to include the whole of the K^{39} peak. Thus we can collect about a milligram of K^{39} every seven hours, and the Kunsman catalyst source will last about 40 hours at this rate. Although we have been concentrating on potassium, we have, at the request of several workers on nuclear disintegration, collected several one-microgram samples of Li^6 and Li^7. At the temperature at which our heater could run, spodumene gave only a few microamperes current, and a Kunsman catalyst was found more suitable. The lithium peaks are separated about 3 cm in space, and the deposit on platinum foil is a bluish color which fades to white when exposed to HF fumes and warmed. The collection of adequate samples of K^{41} for radioactive work is now under way.

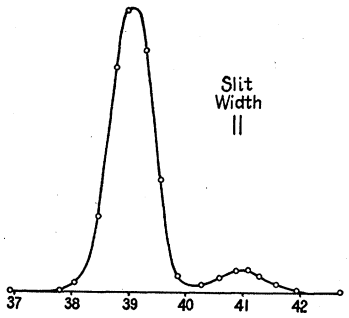

FIG. 4. K^{39} and K^{41} peaks with source at 1100°K, accelerating voltage of 2350 volts, slit width of 0.5 mm and vacuum about 5×10^{-5} mm Hg. Almost entire width of peaks is due to lateral thermal velocity of ions. With the slit widened to include the entire K^{39} peak the collector current in this case was 0.02 m.a. Raising the source temperature and the accelerating voltage increases this to 0.1 m.a. with the same resolution.

One of the authors, L.H.R., has just completed a similar instrument at the Bartol Research Foundation of the Franklin Institute, in which improvements have been made with a view to extending the range to somewhat heavier elements. We wish to thank Mr. Brower of the Astrophysics Shop for his skillful construction of the Pasadena instrument, and Dr. A. Keith Brewer of the Fixed Nitrogen Research Laboratory for a supply of Kunsman catalysts. Among those who worked on the preceding instrument should be mentioned Dr. Dinsmore Alter and Dr. H. M. Evjen.