AN ELECTRO-STATIC BETA-RAY SPECTROMETER, USING A SPHERICAL CONDENSER

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INTRODUCTION

THE theory of a focussing device for electrons using the inverse first power radial electrostatic field within a cylindrical condenser was developed by Hughes and Rojansky (1929), who showed that a narrow diverging beam from a point source is refocussed at a point with angular separation of 127° from the source. A beta-ray spectrometer based on the principle was used by Backus (1945) and later in a modified form, using the second focus at 256°, by Thosar (1949). The latter also discussed the use of the inverse second power radial field between two concentric hemispherical shells and suggested a possible design for a beta-ray spectrometer of high luminosity, based on this principle, the theory of which was given earlier by Purcell (1938). Browne *et al.* (1951) have recently used a spherical electrostatic analyzer for measurement of nuclear reaction energies.

While the cylindrical condenser type of spectrometer is essentially a two-dimensional device, the spherical condenser type is a three-dimensional one and is, therefore, capable of giving very much larger transmission. A spectrometer using a spherical condenser has been constructed in this laboratory for work in the lower range of electron energies and this paper describes the instrument and its performance as tested by artificially accelerated electron beams.

THEORY OF THE INSTRUMENT

Considering two concentric spherical shells of radii r_1 and r_2 respectively, differing in potential by P, the radial field at any point within the electrode space given by radius vestor r, is X, where

$$X = P \cdot \frac{r_1 r_2}{r_2 - r_1} \cdot \frac{1}{r^2}.$$

Following a line of treatment similar to that of Hughes and Rojansky for the cylindrical condenser, the following results can be readily obtained for this type of inverse, second power, radial field.

(*a*) An electron starting from a point on the medium sphere of mean radius r_0 and projected into the field perpendicular to the lines of force, will continue to move along the circular orbit of radius r_0 when its energy E in electron volts and potential difference P in volts on the electrodes satisfy the following relation.

$$E = k \cdot P$$

where the instrumental constant $k = \frac{1}{2r_0} \cdot \frac{r_1 \cdot r_2}{(r_2 - r_1)}$.

This is true of any central section of the electrodes and means that electrons of the right energy from a point source situated midway between the electrodes will travel along circular orbits over the medium sphere and will all meet at the opposite end of the diameter, the point of focus.

(*b*) It can be shown that in any given central section, the twin orbits of electrons of the right energy but making the small angle of divergence $\pm \alpha$ with the median circular orbit will also be refocussed, to a first approximation, at the focal point *i.e.*, at the pole opposite to the source. Actually there is a second order aberration of the focal position for these divergent orbits, where the departure from perfect focussing is $2\alpha^2 r_0$.

(*c*) The resolving power is obtained by calculating the spread of energy dE of the electrons that will be admitted through the width of this focal aberration, *i.e.*, $2r_0\alpha^2$. This gives the resolving power $\frac{dE}{E} = \alpha^2$.

In obtaining the above results, the relativity change of mass with velocity is neglected.

(*d*) The transmission of the instrument will be determined by the angle of divergence 2α, over which, in any central section, the electron beam is admitted through the slit system and the angle θ, giving the useful section of the sphere. In practice, it is not possible to use the complete hemisphere for collection of particles and some 25° section at each edge has to be left out, to reduce distortion due to the edges. Also the angle of divergence α has to be small, to keep the focal aberration at a small value.

CONSTRUCTION OF THE INSTRUMENT

Fig. 1 is a vertical section of the vacuum chamber with electrodes in position. The cylindrical vessel T is made of brass, ¼″ thick, and has internal diameter 15″ and height 11″. The upper lid, made convex for better mechanical strength, is removable and fits into the main chamber by means of a rubber gasket. An ionization gauze head can be inserted through an

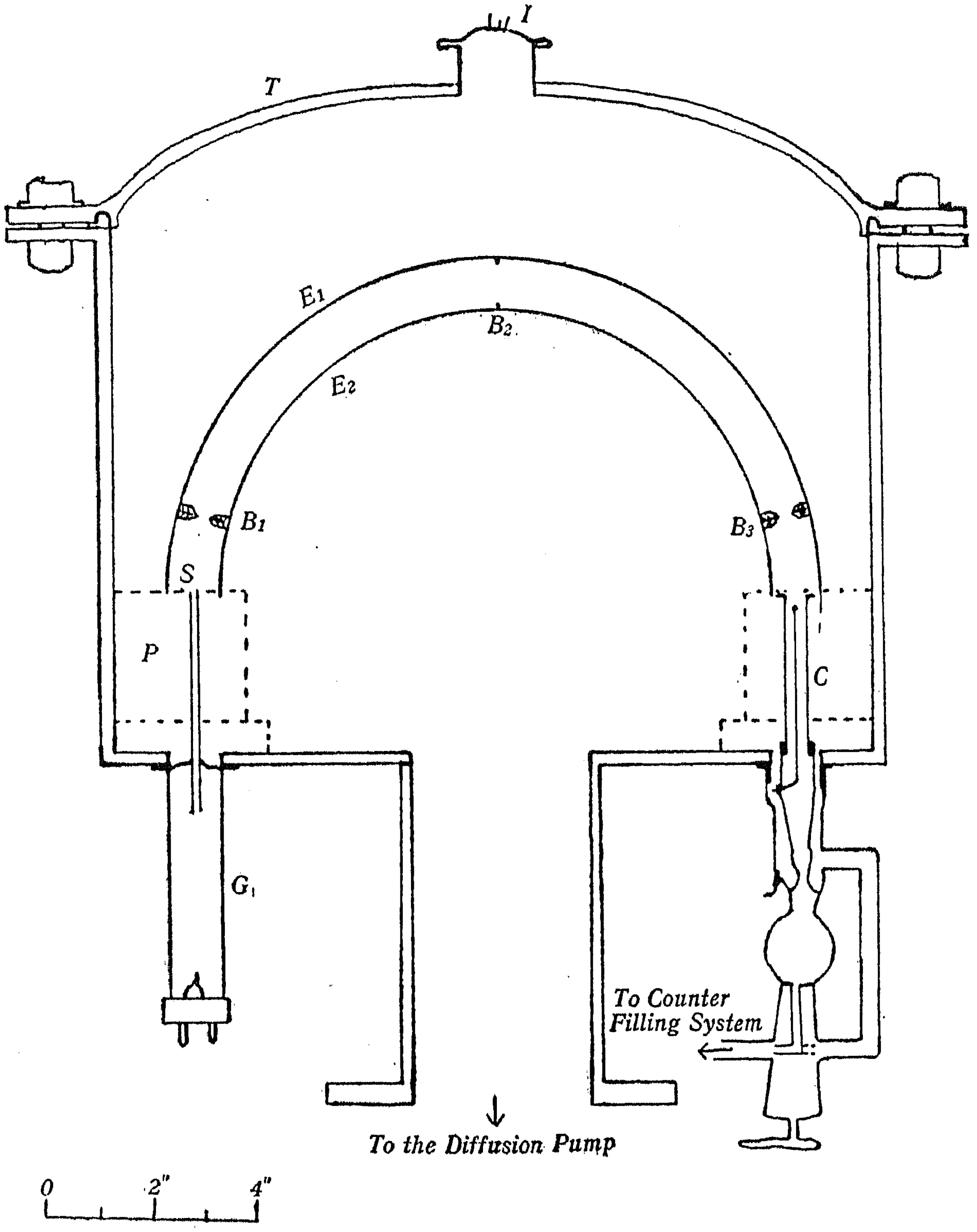


FIG. 1. Vertical Section of the Spectrometer

opening at the top of the lid, for measurement of pressure. Evacuation is by means of a forepump and a three-stage oil diffusion pump. The exit tube leading to the top of the diffusion pump is fitted at the centre of the bottom plate of the chamber. Pressures of the order of 10^{-5} mm. are obtained and this is adequate as the length of orbit from source to focus is about 19″. De-humidification and good vacuum conditions are, however, a special need for this device as high voltages over narrow clearances have to be maintained and spurious electrical discharges must be prevented.

The electrodes E_1, E_2 are two hemi-spherical shells, made out of brass, 1/32″ thick. The inner radius of the outer sphere is 6 + 7/16″ and that of the outer surface of the inner sphere is 5 + 9/16″. The mean electrode distance is $\frac{7}{8}$″, which is estimated to be true to within 1/16″. Care was taken to have those surfaces well polished and free from sharp points to prevent electrical discharge at high voltages. The base P, on which the two electrodes are mounted consists of six perspex blocks, 2″ thick, equally spaced and cemented onto a perspex ring, which just fits inside the vacuum chamber and rests on the bottom plate. Concentricity of the two spheres is ensured, in the first place, by two accurately spaced circular grooves on the blocks into which the electrodes fit. Also the three slits B_1, B_2 and B_3, made out of perspex were so machined that their outer surfaces, in contact with the electrodes have the required curved shape to give a close fit between the electrodes. These perspex baffles, therefore, also serve as spacers between the electrodes. The central slit B_2 is midway between source and the focus, and is in the plane of symmetry. The two slits B_1 and B_3 unlike B_2 are at an angular distance of 15° from the source and the focus respectively. Considerable care had to be taken in the designing and making of these two slits as each of them occupies the electrode space in three dimensions, in an asymmetrical position. The widths of the slits was arranged, for experiments later described, to be such that the semi-angle of divergence α of the electron beam admitted into any central section of the electrode space was 3° 36′. The aperture in each slit extends over 130° in the middle, which defines the section of the spherical electrode space actually used for focussing, 25° on either side near the edges of the electrodes being left out to prevent distortion due to edge effects. Two alkathene rods fitted into the bottom plate of the vacuum chamber, carry the leads, which supply high voltage to the two electrodes. These leads, not shown in Fig. 1 may, however, be easily seen in the photographic reproduction of the instrument.

For the purpose of testing the performance of the instrument with beams of accelerated electrons to known variable energies, a simple design of an electron-gun was used. As the detecting device used was a G.M. Counter which is very much more sensitive compared to any device measuring electron-current, good collimation of the beam was aimed at, at the expense of intensity of the beam. A glass-tube with a tungstan filament sealed into it at the lower end was fixed to the bottom-plate of the tank such that the position of the source within the electrodes was vertically above a sharp point on the filament. A vertical brass-tube, passing through a hole in the bottom-plate, projected into the glass-tube and its end directly facing the filament was covered with a fine wire-mesh. The other end of the tube was covered with a circular disc, with a central aperture of diameter 3/16″ and projected just inside the electrode space, occupying the position of the source. The electrones were accelerated by applying measured negative potential to the filament, the brass tube opposite being connected to the vacuum tank and, therefore, earthed. It was found that no heating of the filament was needed, quite high counting rates being attainable at room temperature, mainly due to field emission from the point on the filament.

Voltage supply to the electrodes is drawn from a voltage doubler circuit, using a 50 k.v. X-Ray transformer and two K.R. 3 rectifier tubes mounted on highly insulated secondary terminals of two filament transformers. There is a 50 Meg ohm resistance chain across the output as delivered by the smoothing condensers and a sensitive milliammeter, reading 1·2 m.a. at full scale, in series with this chain, reads the voltage developed. The voltage is varied by means of a variac auto-transformer, controlling the input to the H.T. transformer and this can be done in steps of 600 volts as read by the meter. A well insulated sensitive micro-ammeter and a 20 Meg ohm resistance is included in each of the two leads supplying the output voltage $\pm$ V/2 to the electrodes. Any leakage current in these meters is an indication of poor vacuum or other faults of insulation, while short-lived flicks in any of the meters serve to indicate spurious electrical discharges within the chamber. It is necessary to ensure that during any run of an experiment with this apparatus, there is a steadily negligible current in each of these micro-ammeters.

In theory, it is only the potential difference between the electrodes that determines the energy of the electrons focussed, but, in practice, it is an advantage to have the two electrodes above and below ground in potential by equal amounts. This makes the source and the counter, midway between the two electrodes, to be at ground potential, which is convenient. Also the difficulties of insulation are comparatively reduced in this arrangement.

A conventional H.T. supply with one rectifier tube and a smoothing condenser was used to give negative potential to the electron gun filament. The arrangement for measurement of voltage was similar to the one described above.

The end window counter C is a brass tube 2″ long and ½″ diameter with a mica window of 1 mg./cm^2 thickness and a closely perforated brass disc on top as a support; 6 to 7 cm. pressure of argon and alcohol filling mixture was used. As can be seen from Fig. 1, the counter can be evacuated first through the main vacuum chamber by turning the three-way tap below the tube supporting the counter. It can then be turned so as to connect the counter to the filling system. The difference of pressure on the two sides of the counter need not, therefore, exceed 7 cm.

PERFORMANCE OF THE INSTRUMENT

(1) The instrument was tested for its focussing properties in the range of electron energies 20 to 40 KeV. A known negative potential E was applied to the gun filament and the voltage $\pm$ V/2 on the two electrodes was slowly increased, keeping the counting rate under observation. The electrode voltage for which the counting rate is at a maximum was carefully noted. About six values of different electron energies were used and a plot was made of electron energy E in KeV against the electrode potential V in K. Volts. Fig. 2 gives the plot, showing that the points lie on a straight

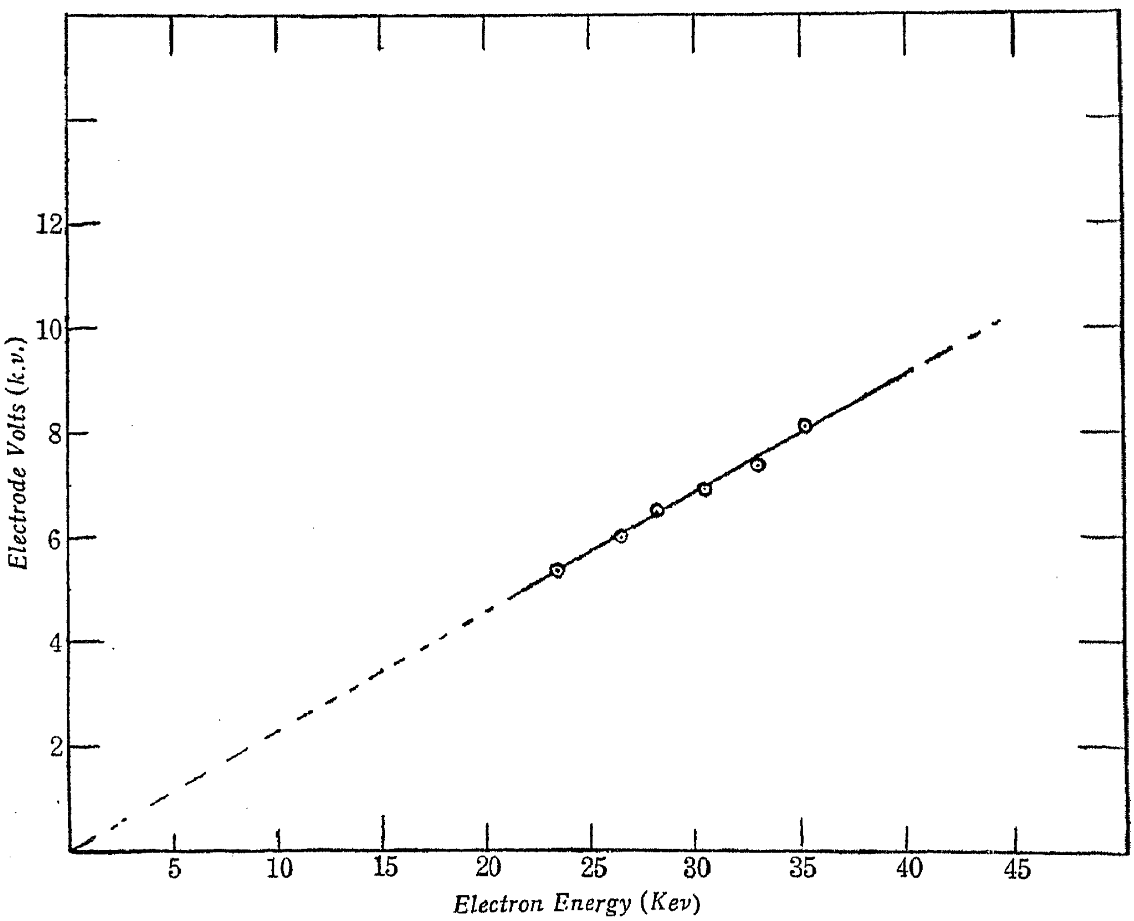


FIG. 2. Etectrode potential difference plotted against elebcron energy

line and that it passes through the origin, as required by the theory. The instrument constant K in the relation E = K.V., comes out to be 4·37.

(2) To obtain a measure of the resolving power of the device, for the particular slit system used, a slight modification in the resistance chain and meter across the high voltage applied to the electrodes was made so that the electrode volts could be varied and read more accurately in smaller steps. The plot of the counting rate against electrode volts for the gun voltage of 26·5 K.V. is reproduced in Fig. 3. To obtain the spread *d*E of energy

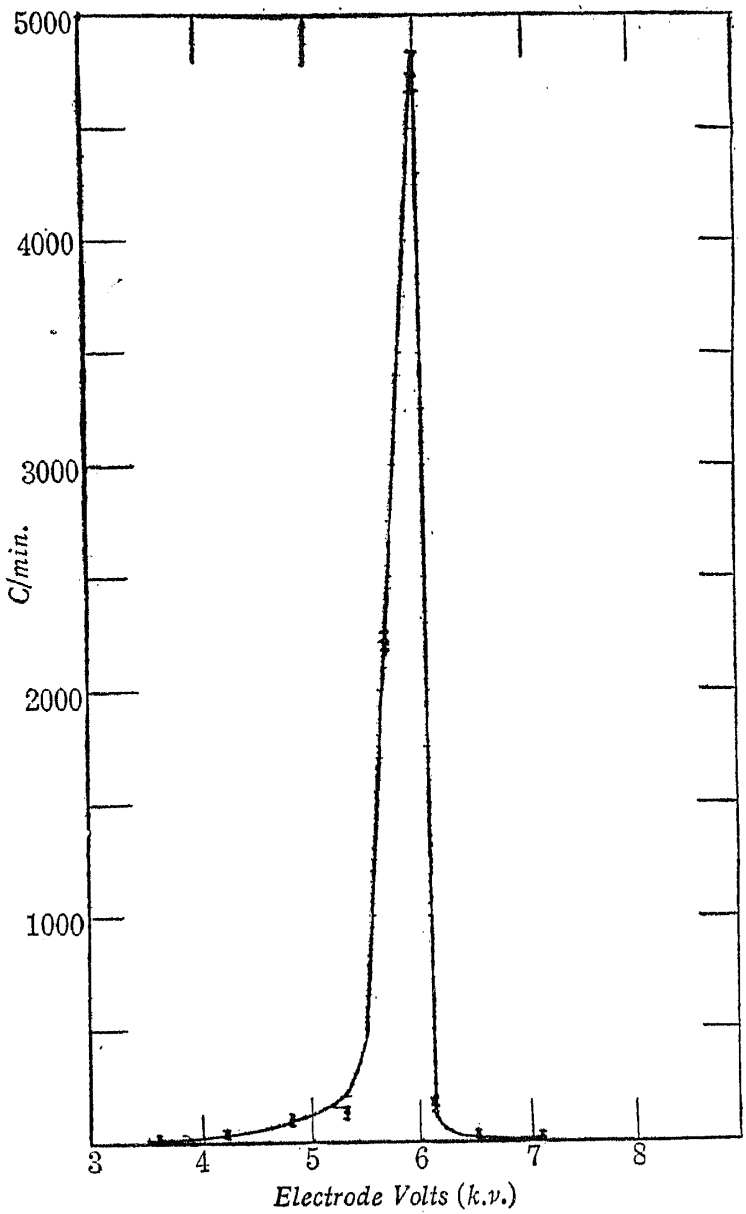


FIG. 3. Counting rate plotted against electrode potential difference for mono-energetic electrons of energy 26·5 KeV.

when electrons of energy E are being focussed, the width of the peak half-way between the base and the maximum has to be measured. It is seen that the two wings of the curve show a little asymmetry, the low energy side showing the effect of straggling of electron energies. This must be due to the scattering of the particles at the electrode walls. This effect will not be shown on the high energy wing of the peak, which is steeper. Obtaining the value of dE from the steeper side of the maximum alone, the resolving power dE/E comes out to be 1·66%, while the use of the overall width gives the value at about 3%. Also, the theory as worked out for a point source is not strictly applicable as the electrons issue out of a circular aperture of diameter 3/16″.

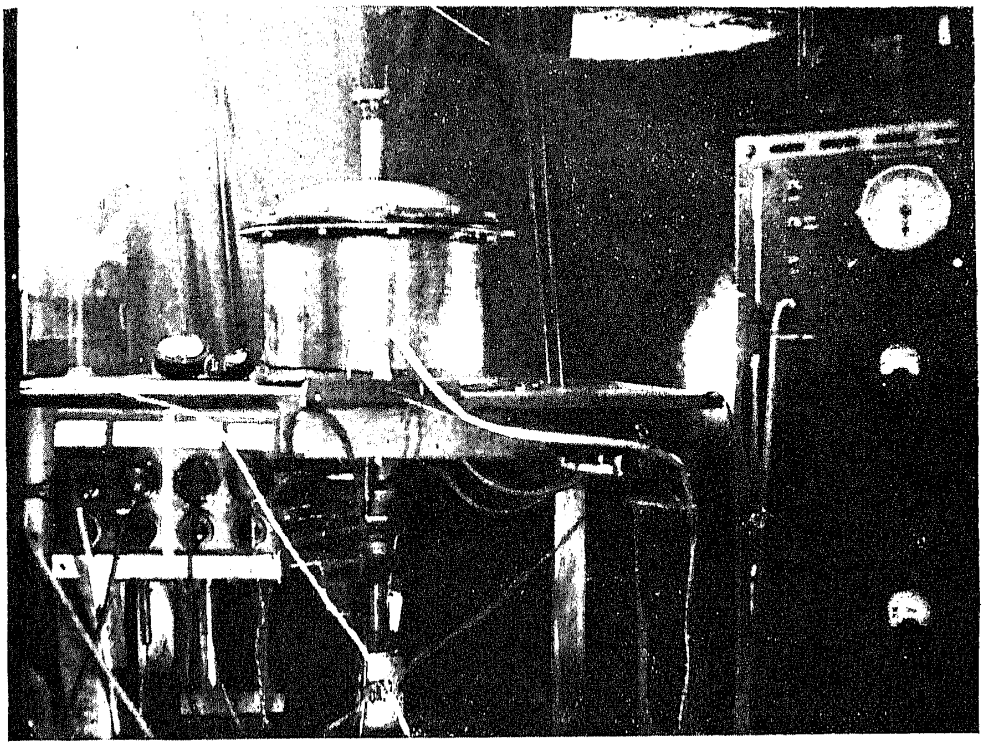
(3) The luminosity is determined by the solid angle over which the beam of electrons is admitted into the focussing space between the spheres. The angle of divergence of the beam in any central section of the spheres is, as already mentioned, $2 \times 3° 36'$ while the useful section of the sphere used is 130°. This gives the solid angle of acceptance as 1/44 of a sphere or 2·4%.

DISCUSSION

The instrument as described above is capable of further improvements in many respects. First, the electrodes should be spun metal spheres giving much greater mechanical accuracy as regards the spacing between them. Also to reduce the effect of scattering from these surfaces, they should preferably be of aluminium. The performance of the spectrometer can be improved by a more accurate voltage supply and voltage measuring device. The main characteristic of the instrument is large luminosity for a given resolving power so that comparatively weak sources may be studied. The upper limit to the electron energy that can be studied is set by the high voltage that can be steadily maintained on the electrodes, without spurious discharges taking place. Also there is the effect of defocussing due to relativity change of mass at higher energies, which has been referred to by Purcell (1938). At very low energies, the effect of the earth's magnetic field on the orbits may have to be taken into account.

SUMMARY

An electrostatic beta-ray spectrometer using a spherical condenser has been constructed for study of weak sources, and its performance has been tested with accelerated electron beams. The device, which is intended for low energy range of electrons, has, for the slit system employed, the resolving power of 1·6% with transmission 1/44 of a sphere which compares



Electro-static Beta-ray Spectrometer

favourably with that in other types of spectrometer. The electron energy E (in KeV) focussed is 4·37 times the voltage V. in K.V. on the electrodes.

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Note added in proof:—Yoshiyuki and Kobayashi have recently published a letter, describing a similar instrument, in *Journ. Phys. Soc.*, Japan, 1953, **8**, No. 1, January–February.