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Variable Field Beta-Ray Spectrometer-Spectrograph

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The design and performance of a high source type, 180° focusing, variable field, beta-ray spectrometer-spectrograph are described. Some details regarding the measurement of magnetic field, the construction of end-window Geiger counters, and the preparation and thickness measurement of thin Formvar counter windows are also discussed.

INTRODUCTION

A VARIABLE field 180° type beta-ray spectrometer-spectrograph has recently been constructed and placed in operation at Kansas State College. The instrument (Fig. 1) is presently operated as a variable field spectrometer of 15-centimeter radius, with data obtained by Geiger counter detection; or as a "fixed field" spectrograph with data obtained through the exposure of photographic film.

THE MAGNET

All the magnet iron, including yoke, pole pieces, and bolts were fabricated of Armco iron which had been annealed at 1675°F by the Armco Steel Corporation. The pole pieces were forged of iron selected from the center section of an ingot for greatest homogeneity. Yoke members were $5\frac{1}{4}$ in. square. The length of the two horizontal members was 50 in. while the vertical members were 13 in. long. Pole pieces were $5\frac{1}{4}$ in. thick by $16\frac{3}{4}$ in. square. The total weight of iron was 1400 pounds.

The magnetic field was generated by two coils, one mounted on each vertical yoke member, operated in parallel in both electrical and magnetic circuits. The

coils were wound and impregnated by the General Electric Company,¹ onto coil forms fabricated from $\frac{1}{8}$ -in. brass sheet. Each coil was wound with 20 000 turns of No. 20 (35.5 mil) heavy Formex wire. The coil resistance averaged 545 ohms at 25°C . Before mounting on the magnet yoke, a current of 500 milliamperes produced a temperature rise of 35°C at the inside surface of coil form. This rise was consistent with a dissipation of 0.004 watt per square inch per degree centigrade; significantly different from the value of 0.006 watt per square inch per degree centigrade quoted by Roters² for an impregnated coil. When the coils were mounted on the magnet, with sheets of aluminum driven into the gap between iron and coil form for better heat transfer, 500 milliamperes of current in either coil (corresponding to a total excitation current of 1 ampere) caused a temperature rise of 24°C at the inside of the coil form.

Aside from normal machining, no special effort was made to assure a smooth finish on any butting surface. The pole faces were ground in a large lathe using a tool post grinder. When the magnet was assembled with faces parallel, it was found that the pole faces were inadvertently dished, the gap separation being 2.506 in. at the center regularly decreasing to 2.501 in. at the corners in concentric circles, presumably due to progressive wear of the grinding wheel. Copper shims were used to obtain parallelism of the pole faces.

With excitation coils connected in parallel, an initial check showed the field in the gap to be quite uniform within a single traverse normal to the plane of the yoke, but traverses parallel to the plane of the yoke showed that the field was tapered, with the nonuniformity decreasing from 20 percent at fields of about 10 gauss to 4 percent at fields of about 270 gauss. An electrical shim consisting of a 50-ohm rheostat in series with one coil sufficed to eliminate the taper and to decrease the field nonuniformity, in that part of the gap at least one gap width from the edge of the pole piece, to within $\frac{1}{2}$ percent at all fields measured, ranging from 10 to 300 gauss. The uniformity was better at high than at low field.

A "hysteresis loop" for the magnet has been plotted

FIG. 1. Beta-ray spectrometer-spectrograph, showing magnetometer, magnetic circuit, vacuum chamber, and Geiger counter.

¹ General Electric Company, Apparatus Department, 840 South Canal Street, Chicago 80, Illinois.

² H. C. Roters, *Electromagnetic Devices* (John Wiley and Sons, Inc., New York, 1941), p. 185.

in Fig. 2, for excitation currents up to 250 milliamperes. A peak field in the gap of 515 gauss generated a remanent field of 15 gauss. By the usual procedure of progressively diminishing the amplitude of successive hysteresis loops the remanent field in the gap could be readily reduced to a fraction of a gauss. At low fields, bumps due to non-uniform remanent behavior of the iron might be a source of difficulty. Such behavior would be noted most easily through shifts in position of internal conversion lines on beta-ray spectrograms made at low fields. No such shifts have been observed although repeated spectrograms of the same source have been exposed at 85 gauss.

FIG. 2. "Hysteresis loop," showing the field in the gap as a function of excitation current.

A comparison of the measured field within the gap with values calculated by sophomore methods showed that only 24 percent of the total ampere turns were effective in producing useful field, the remaining ampere turns generating fringing field.

The magnet was powered by a 72-volt bank of heavy duty truck-type storage batteries, installed in an interior basement room, and apparently subject to only seasonal temperature variations. Current control has been obtained by means of a bank of tubular variable rheostats normally connected in series as shown in Fig. 3. When the field was to be zeroed, it was found

FIG. 3. Current through the magnet coils is controlled by series resistors $R-1$ through $R-5$ (22, 360, 2900, 5950, and 5680 ohms, respectively). $R-6$ is an electrical shim of 50 ohms which serves to uniformize the field. Since the minimum field obtainable with the series combination is 10 gauss, switch A is closed for field zeroing purposes and $R-5$ is operated at the zeroing "potentiometer."

convenient to close the switch "A" and to operate R_5 as a "potentiometer."

With diurnal variations in laboratory temperature held to about 10°F by thermostatic control of the heating supply, no difficulty has been encountered in manually monitoring the magnetic field to within one part in a thousand for periods of one month, by checking the field at intervals of 6-12 hours. As a result, operation of the magnet as a "fixed-field" 180° focusing beta-ray spectrograph, using photographic detection, has been quite feasible.

Measurement of Magnetic Field

Measurement of magnetic field intensity has been accomplished through comparison of the alternating voltages generated by a pair of spinning coils. Similar arrangements have been reported elsewhere.³ An Elnico⁴ hysteresis motor (1/60 hp, 1800 rpm) with double shaft extension was directly coupled to two $\frac{5}{8}$ -in. diameter Lucite shafts carrying similar pick-up coils. Each coil contained 5008 turns of No. 49 (1 mil) single Formex wire, wound on a Lucite bobbin. The average dimensions of each coil were 1 in. long by $\frac{7}{16}$ in. wide by $\frac{1}{4}$ in. thick. Each coil had a resistance of 10 300 ohms. The reference signal was obtained from a coil mounted in the end of a Lucite shaft 5 in. long, rotated in the field of a permanent (magnetron) magnet which had been provided with enlarged iron pole tips ($3\frac{1}{2}$ in. diameter by $\frac{1}{4}$ in. thick) to eliminate harmonic components which might otherwise be generated in the reference field. The reference magnet provided a field of 825 gauss. The second coil was mounted on a Lucite shaft 20 in. long, inserted into a corner of the unknown field. This shaft was enclosed in a brass tube of 1 in. outer diameter by $\frac{3}{32}$ -in. wall which was provided with a stationary bronze bearing at its extreme end. A $\frac{1}{4}$ -in. pin, made from linen-filled phenolic mounted in the end of the long Lucite shaft, rotated in this

³ L. M. Langer and F. R. Scott, *Rev. Sci. Instr.* **21**, 522 (1950); W. R. Lamb and R. C. Retherford, *Phys. Rev.* **81**, 222 (1951); Brown, Bendel, Shore, and Becker, *Phys. Rev.* **84**, 292 (1951); A. Hedgran, *M. Siegbahn Commemorative Volume*, p. 255, Uppsala (1951).

⁴ Electric Indicator Company, Stamford, Connecticut.

bronze bearing. This design eliminated possible eddy current difficulties which might be associated with the motion of metal objects in a magnetic field.

The 30 cycle signals were taken out through coin silver slip rings and alloyed gold wire brushes. A slip ring assembly from the Bendix radiocompass⁵ in which a pair of silver slip rings were molded to a Bakelite tube of $\frac{3}{8}$ -in. i.d. was ideally suited to this purpose. Twin brushes on each slip ring consisting of alloyed gold wire⁶ completed the arrangement. Signals from the two pickup coils were compared on a Helipot potentiometer (50 000 ohm, 15 turn, 0.1 percent linearity), the unbalance current amplified by a highly peaked 30-cycle amplifier and observed on a cathode-ray oscilloscope, driven by a linear sweep. Through visual observation of the signal pattern the residual brush noise and pickup could be eliminated from the balancing operation, and a change of signal strength of one part in 10 000 could readily be detected. Coarse phasing adjustments were made initially by rotating the shafts of the two coils with respect to each other, but fine phasing control was accomplished by rotating the permanent magnet by means of a pair of opposing micrometer screws each time a balance was made.

To minimize interference from the variable fringing field of the electromagnet, the reference magnet was located some 75 cm from the edge of the pole pieces, with its field direction perpendicular to the direction of the electromagnet's field. Variations in the earth's magnetic field were neglected in comparison to the reference field of 825 gauss. Consequently no magnetic shielding of the reference magnet was employed. The entire spinner assembly was mounted onto a $\frac{1}{4}$ -inch brass plate, which was screwed to a 1-inch plank of well-seasoned oak, to reduce vibrations.

Calibration of the magnetometer has been accomplished through the internal conversion electrons of Cs^{137} and RaD , and through the zero position of the

FIG. 4. Spectrograph insert. A source and a developed film of Cs^{137} are shown in position.

⁵ Bendix Radio Part No. A29711, Collector Ring, Bendix Radio, Baltimore 4, Maryland.

⁶ Ney Oro No. 28a, 0.015-in. diam, J. M. Ney Company, 71 Elm Street, Hartford, Connecticut.

FIG. 5. Spectrometer insert. All baffles are of Lucite painted with conducting paint. The magnetometer probe is inserted through the port at lower left to within an inch of the baffle.

Helipot potentiometer. The magnetometer may be seen in position in Fig. 1.

Camera Inserts

Inserts have been provided for use of the magnet as a beta-ray spectrometer of 15-cm radius, and a beta-ray spectrograph in which electrons of radius between 4 and 16 cm may be recorded on photographic film. The design of the spectrograph insert was patterned after the spectrograph of Rutherford and Robinson, while that of the spectrometer insert was patterned after Lawson and Tyler. The same source frame was used in both inserts, sources being mounted as dry powder on Scotch tape, or as solutions deposited on Scotch tape or thin film backing as required. The spectrograph insert was constructed of aluminum and was provided with (Lucite) slit jaws. In Fig. 4, the insert has been photographed with its light-tight cover removed, showing a powder source mounted in position, and a developed spectrogram of Cs^{137} in place in the film position.

The spectrometer insert, illustrated in Fig. 5, was laid out on an aluminum base plate $\frac{1}{8}$ in. thick and was provided with an aluminum cover plate which has been removed in the photograph. Eight inches of lead separated the source from the Geiger counter. All other construction in the insert, including baffles, slit jaws, and facing for the lead block, was of Lucite, painted with a conducting paint made from flake graphite and clear glyptal. Openings were provided in the insert at the upper left-hand corner for the Geiger counter, in the lower right-hand corner for the pumping port, and in the lower left-hand corner for the field measuring probe, which is inserted into a recess in the vacuum chamber. The electron trajectories were confined to the center portion of the magnet. Source and slit were coplanar, and the limiting baffle was located in the center of the electron orbits. Slit jaws were made of

FIG. 6. Spectrum of Cs^{137} (lower scale) obtained with a uniform source and slit 1 mm wide and $1\frac{5}{8}$ in. high. The upper scale accompanies the expanded internal conversion electron spectrum to illustrate the line profile and resolution obtained.

$\frac{1}{8}$ -in. Lucite and were provided with quarter round edges to minimize transmission difficulties.

The determining parameters in the conditions for optimum operation of a spectrometer of this type, as stated by Persico and Geoffrion,⁷ are the source height and the radius. The magnet gap width was reduced by the thickness of the walls of the vacuum chamber, the chamber lining, the source frame and wall thickness of the Geiger counter, so that a gap width of $2\frac{1}{2}$ in. was translated into a usable source height of $1\frac{5}{8}$ in. The prescribed optimum conditions implied that this source height in a spectrometer of 15-cm radius required a source and slit width of 1.15 mm, an angle ϕ_0 of 3.5° for limiting trajectory (or a full width of 1.86 cm for the central baffle). The spread η of the instrument was calculated to be 0.58 percent in terms of full width at half-maximum, and the luminosity L^* (the fraction of the emitted particles collected by the Geiger counter with these slit and baffle settings) was calculated to be 0.26×10^{-3} .

The resolution, transmission, and line shape were determined experimentally with a source of Cs^{137} deposited on the nonadhesive side of a 1-mm strip of Scotch tape. Insulin was used as wetting agent. The source uniformity was checked autoradiographically. The source height was $1\frac{5}{8}$ in. The exit slit and center baffle were set at 1 mm and 1.86 cm, respectively. The height of the Geiger counter opening was $1\frac{5}{8}$ in. For these conditions the calculated spread and luminosity were $\eta = 0.53$ percent and $L^* = 0.22 \times 10^{-3}$.

Experimentally, collection was determined by measuring the electron counting rate in an end window counter in air at a distance from the source sufficiently great that the electron counting rate (corrected for window and air absorption) obeyed the inverse square law. The rate of emission of K conversion electrons into a 4π solid angle was calculated using a total

conversion coefficient $\alpha = 0.12$, a K conversion coefficient $\alpha_K = 0.097$, and a relative intensity of 5 percent for the 1.19-Mev branch. The peak counting rate of the K conversion line in the spectrometer was divided by the total rate of emission of K electrons to give the luminosity L^* .

The spectrum obtained for Cs^{137} is illustrated in divided form in Fig. 6. The luminosity obtained was $L^* = 0.41 \times 10^{-3}$ and the spread was $\eta = 1.0$ percent, both being twice as great as calculated. It is interesting to note that narrower line profiles have been obtained in this instrument with wider baffle openings, but autoradiography has indicated that the sources responsible for the narrower lines were quite nonuniform.

Geiger Counters

End-window counters for use with the spectrometer were provided with a flange to mount onto the vacuum chamber cover plate. A 2-in. o.d. by $\frac{1}{8}$ -in. wall brass tube 5 in. long was provided with a mounting flange and face plate as shown in Fig. 7. A 1-in. long center wire of 8-mil Nichrome was spotwelded to a 50-mil tungsten support lead which was sealed into a glass stem. The stem, carrying both center wire and a glass filling tube was "waxed" in place onto the brass counter body with a thermoplastic resin.⁸ The Nichrome center wire was provided with a large (2-3 mm diameter) aquadag coated soft glass bead at its extreme end, following Papineau's recommendations.⁹ The bead was located about one tube radius behind the window. Thin Formvar windows were mounted on the window support face and were supported by 25-mesh copper lectromesh screen. Counters were filled with pure ethyl alcohol vapor, maintained at a constant pressure of 1.2 or 3.5 cm by immersing a container of liquid alcohol open to the Geiger tube in a bath of melting

FIG. 7. Geiger counter assembly showing tungsten support wire, Nichrome center wire, glass sleeve, and bead and other details.

⁷ E. Persico and C. Geoffrion, *Rev. Sci. Instr.* **21**, 945 (1950); C. Geoffrion, *Rev. Sci. Instr.* **20**, 638 (1949).

⁸ Gelva V 2 $\frac{1}{2}$ Shawinigan Products Corporation, Empire State Building, New York, New York.

⁹ A. Papineau, *J. phys. et radium* **12**, 667 (1951).

FIG. 8. Electron transmission through 0.004-in. copper lectromesh screen (25 mesh, 50 percent transmission) as a function of electron momentum.

ice or of flowing tap water. No problems attributable to window charging have arisen. Plateaus of width 150 volts and slopes up to 15 percent rise per 100 volts were readily obtained, with usable stability. Corrections must be applied to measured counting rates at high energies for the variable transparency of the lectromesh backing. The relative transmission of 0.004-in. thick copper lectromesh as a function of energy has been plotted in Fig. 8. A convenient gasketed lectromesh assembly was fabricated from disks of $\frac{1}{16}$ -in. brass and $\frac{1}{32}$ -in. polythene gasketing (the latter provided with openings conforming to the front face of the Geiger counter) in the following way. The three components (lectromesh, brass, and polythene) were clamped to a flat brass plate and gently heated. The thermoplastic polythene bonded the metal members together without distortion of the lectromesh, thereby providing a smooth, flat support face for the thin film window of the counter.

Thin Films of Formvar

A simple and satisfactory technique has been evolved for the preparation of thin films of Formvar. According to Chen,¹⁰ Formvar films were twice as strong as Nylon (a rather inconvenient film-making material) and some seven times as strong as Zapon. With Formvar, neither solution nor storage has presented any problem. A

¹⁰ J. R. Chen, Rev. Sci. Instr. 21, 491 (1950).

stock solution of about 10 grams of Formvar 15-95E (Shawinigan Products Company) in 150 cc of ethylene dichloride has been found convenient. Films have been most readily prepared on freshly drawn tap water, by dropping a single drop of solution (diluted, if necessary) onto the water near the edge of the container. The multicolored, wrinkled film forming at the drop position has been generally unsuitable, but a rather wide, thin, unwrinkled, and almost colorless margin is formed from which single or double films of good homogeneity could be obtained. Several films have been picked up on a single frame to form a window of desired thickness. For double films, wire frames made by spotwelding a half-circle to a length of straight Nichrome wire have been most convenient. For single films, frames made from sheet aluminum in which a relatively wide aluminum margin was provided were most useful. Single thicknesses down to about a few micrograms per square centimeter have been conveniently obtained.

The thickness of thin films may be obtained from white light interference colors, provided that a color calibration has been made. By overlaying single films a template containing 1 to 16 single layers of Formvar has been prepared. With layers of uniform thickness the template may be calibrated by visual examination in monochromatic light for, in normal incidence, the reflectance is a minimum when the optical path length for the internally reflected ray equals an integral number of wave lengths. Harris and Beasley¹¹ have shown that the refractive index determined from reflectance measurements on thin collodion films is reasonably consistent with that determined for the bulk material. A reflective null at 11 film thicknesses was obtained in the light of a sodium lamp. Since the refractive index and specific gravity of Formvar were 1.5 and 1.2, respectively, this corresponded to a thickness of 180Å and a density of 2.1 micrograms per square centimeter for a single thickness.

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¹¹ L. Harris and J. K. Beasley J. Opt. Soc. Am. 42, 634 (1952).