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EXPERIMENT 10. ANGULAR DISTRIBUTION OF SLOW NEUTRONS[12]

A BF_3 counter 6 in. long is placed in a cadmium-covered pipe which is approximately 1 ft long and 1 in. in diam. The pipe is held directly above the plug of the central facility and rotated to different angular positions. The count rate for the various angles is recorded and compared with the theory.

Other experiments, similar to the ones described above illustrating the fundamental properties of neutrons which are useful in nuclear and reactor physics research, can be performed with this apparatus. The equipment described in this paper should prove an excellent starting point for a nuclear laboratory.

[12] E. Amaldi and E. Fermi, Phys. Rev. **53**, 1020 (1938).

Demonstration of the Electric Fields of Current-Carrying Conductors

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The making of the two-dimensional printed circuit type models of current-carrying conducting systems and the use of these models for demonstrating the electric fields of current-carrying conductors is described. The models are produced by drawing the systems under consideration on glass plates using a transparent conducting ink. The electric lines of force inside and outside the elements of these models are demonstrated with the aid of grass seeds strewed upon them.

I. INTRODUCTION

WHILE there are several well-known methods for demonstrating the structure of electrostatic fields,[1] and numerous electrostatic field maps and lines-of-force pictures can be found in physics textbooks, no generally known methods for demonstrating the structure of the electric fields of the current-carrying conductors appear to exist, and the diagrams of these fields can usually be found only in the highly specialized literature. This leads to the undue emphasis on electrostatics in presenting the electric fields in the ordinary physics courses and frequently causes the students to remain virtually ignorant of the structure and properties of the electric fields inside and, especially, outside the current-carrying conductors of even the simplest geometry. The development of a simple and effective method for demonstrating and illustrating the structure and properties of the electric fields of current-carrying conductors is therefore very desirable, especially in view of the fact that the occurance of these fields in laboratory, in nature, and in industry is at least as frequent as that of the electrostatic fields.

A method for demonstrating and studying the stationary electric fields of the current-carrying conductors with the aid of the printed circuit-type models is described in this paper.

II. PREPARATION OF MODELS

Transparent two-dimensional models of various conducting systems are made on glass plates using a transparent conducting ink. Although the models can be simply drawn with an ordinary brush, much better results can be obtained by following the procedure outlined below.

A glass plate is thoroughly cleaned with soap and water and rinsed in a Kodak "Photo-Flo" solution diluted 1 to 200. After drying the plate, the ink is poured on it so as to form a small pool in the middle of the plate, and then, by slowly inclining the plate to one side or the other, the ink is made to spread evenly over the entire

[1] See, for instance, R. W. Pohl, *Elektrizitätslehre* (Springer-Verlag, Berlin-Göttingen-Heidelberg, 1955), 15th ed., pp. 17–54 (electrostatic-force-line pictures formed by gypsum crystals on glass plates); Physical Science Study Committee, *Physics* (D. C. Heath and Company, Boston, 1960), p. 467 (electrostatic-force-line pictures formed by grass seeds suspended in an insulating liquid); Ernst Weber, *Electromagnetic Fields* (John Wiley & Sons, Inc., New York 1950), Vol. I, pp. 183–195 (electrolytic tank and other analogy methods).

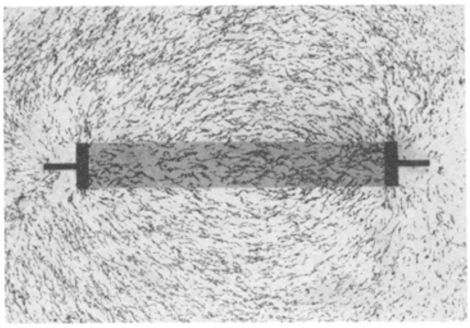

FIG. 1. Electric field of a straight conductor.

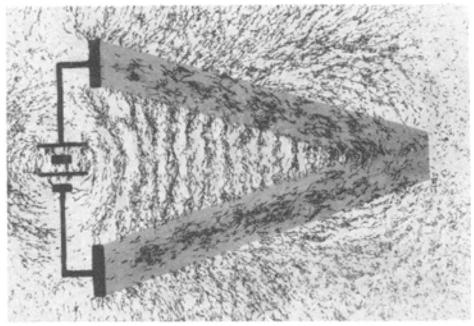

FIG. 2. Electric field of two intersecting straight conductors.

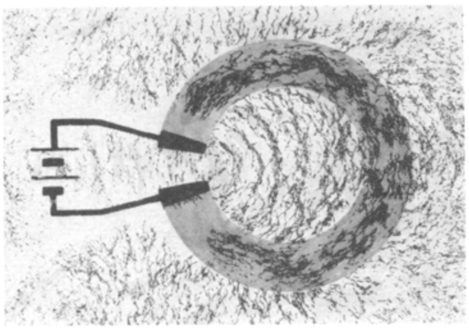

FIG. 3. Electric field of a circular conducting ring (hollow cylinder).

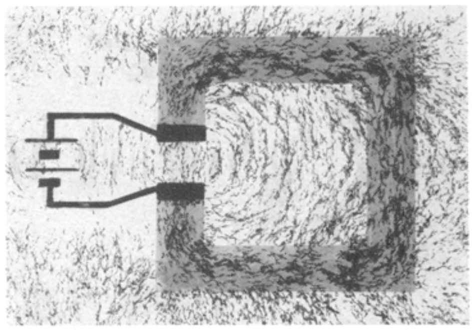

FIG. 4. Electric field of a square-shaped conducting ring (box).

plate. The plate is dried again and is laid, inked-side up, over the drawing of the conductor under consideration. The drawing is then "transferred" to the plate by washing off the ink from the plate, with the aid of a piece of wet filter paper, everywhere except in the places directly over the drawing. The electrodes, the lead wires, and the batteries (if desired) are subsequently drawn on the plate with India ink using a brush. This completes the model, which essentially constitutes a printed circuit with the normal conductors represented by the conducting ink and the perfect conductors (electrodes and lead wires) represented by the much better conducting India ink.

In order to be able to establish the electric connection between a model and a power supply, two thin aluminum foil ribbons (Christmas-tree decorations) are fastened with an adhesive tape to the edge of the glass plate on which the model is made. The length of the ribbons should be such that their free ends can be conveniently laid over the battery terminals of the model.

A convenient size for the models is 4×6 in., and that for the glass plates is 10×12 in.

There is a very considerable difference in the conductivity and transparency of various inks, water colors, and paints. After several trials it was found that the most suitable material for the above described models appears to be Schaeffer's #04 permanent red ink diluted 1 to 1 with water.

III. DEMONSTRATION OF THE FIELDS

In order to demonstrate the electric field of a current-carrying conducting system, the model of this system is placed in a "Vu-graph" projector, where it is supported by four small blocks of insulating material, each about $\frac{1}{2}$ in. thick. The free ends of the aluminum ribbons are then laid over the battery terminals of the model so as to be in good contact with them, and a high-voltage power supply is connected to the ribbons at the edge of the glass plate with the aid of the alligator clips. The power supply should be capable of producing about 10^4 v and should, for safety reasons, be of a low-current type. Very good results were obtained using a Du Mont high-voltage power supply type 263-A (all pictures in this article were obtained with this power supply). Also very good, although somewhat less conveni-

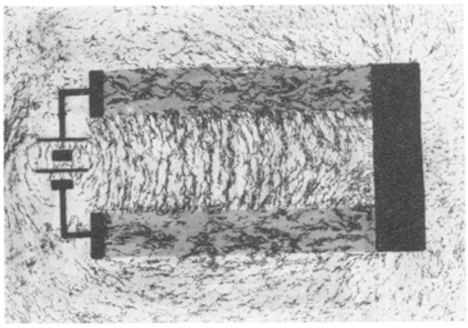

FIG. 5. Electric field of a shorted symmetric transmission line.

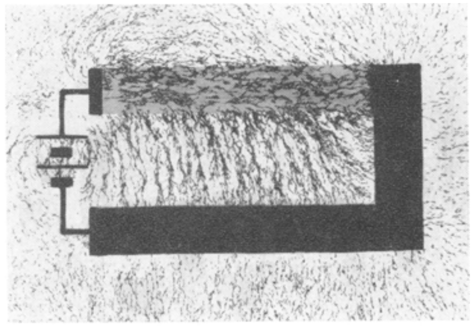

FIG. 6. Electric field of a shorted asymmetric transmission line.

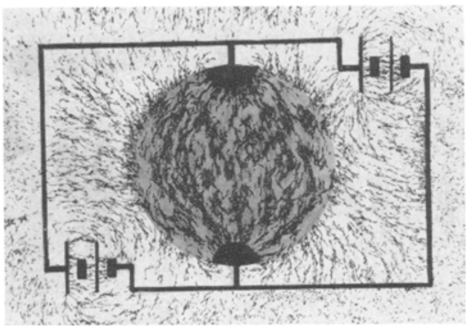

FIG. 7. Electric field of a sphere (cylinder) with dipole type connections.

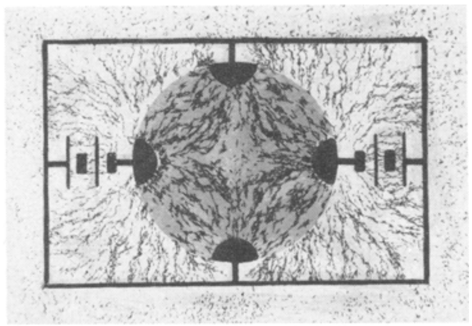

FIG. 8. Electric field of a sphere (cylinder) with quadrupole type connections.

ent, is a small van de Graaff generator (for instance, Welch 1901M).

When the power supply is turned on, and the model is projected on a screen, some fine grass seeds are strewed on the model. The seeds line up in the direction of the electric field and form very distinct patterns of the electric lines of force (some tapping of the plate may be helpful to assist the formation of the patterns). The pictures appearing in this article were obtained by using the Redtop grass seeds.

IV. DISCUSSION

Examples of the lines of force pictures obtained with the above described models are shown in Figs. 1–8 (the aluminum ribbons were removed before taking the pictures).[2] The structure of the fields is clearly visible not only outside the conductors, but, since the conductors are represented by a transparent ink, also inside them. In the actual demonstrations the conductors are red, and the lead wires and electrodes are black. This difference of colors considerably contributes to the effectiveness of the demonstrations. In fact, it seems that even when demonstrating the electrostatic fields, it is much better to draw the conductors with a transparent colored ink, rather than to cut them out, in the traditional manner, from the aluminum foil. Transparent colored ink not only makes the demonstrations more vivid but also makes them more informative, since the seeds in the conducting regions are then clearly visible, and, as they do not form any patterns in these regions under electrostatic conditions, they demonstrate the absence of the electric field in the conductors under electrostatic equilibrium.

The models described here can be used also for a quantitative study of the two-dimensional electric fields of current-carrying conductors. In this case they serve for obtaining the prototypes of the field maps in conjunction with the method of the curvilinear squares.

[2] Additional photographs may be found in Oleg Jefimenko, *Electricity and Magnetism* (Appleton-Century-Crofts, Inc., New York, to be published).