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Author

Rankin, Bayard.

Publication Date

1952-01-21

UNIVERSITY OF CALIFORNIA - BERKELEY

UCRL- 1849

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Radiation Laboratory

Contract No. W-7405-eng-48

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Bayard Rankin

January 21, 1952

Berkeley, California

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Bayard Rankin

Radiation Laboratory, Department of Physics
University of California, Berkeley, California

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In many experiments which investigate microscopic properties of matter, it is necessary to measure angles accurately under the microscope. For instance, to take an example from nuclear physics, suppose a high energy meson passes through a photographic emulsion. The small angular deviations in its track caused by multiple collisions with atomic nuclei will be a function of its mass and ionization. Their average value together with the meson ionization uniquely defines the mass.

Again, suppose the meson collides with a proton at rest in the emulsion. Photographically, the meson track will end abruptly and branch into two. Yet the angles between the tracks will almost always be enough to distinguish the event from the more complex process of nuclear absorption followed by the emission of two charged particles.

The examples are especially pertinent to the main discussion of this paper. A microscope instrument will be described which was designed for making angular measurements on particle tracks. It was developed during a recent experiment on the scattering of high energy mesons in emulsion*. However, this paper is written in the hopes that

* Hugh Bradner and Bayard Rankin, "Fast Meson Interactions in Nuclear Emulsions, Part I: on π^- Mesons," also "Part II: On π^+ Mesons," Phys. Rev., To be Published.

the device will find a variety of uses.

The instrument is a goniometer which makes use of the reflected image of a light source superimposed upon the field of view. It is made up of three concentric cylinders, of which the innermost clamps to the microscope and provides a bearing for the second. The second and third are free to rotate. One holds the eyepiece, one a thin glass strip. In essence, the glass strip, tilted at an angle θ to the plane of the lens, transmits the light of the field of view and reflects the rays from an exterior light source, say a row of needle points. As the glass strip and eye piece rotate through some angle, ϕ , the needle points, if properly placed, appear to pass across the field of view. Their displacement relative to some fixed object in the field is a measure of ϕ .

In order to understand the goniometer more precisely, let us construct a simple mathematical description of an ideal instrument. The instrument will be a glass strip pivoted on the axis of the microscope barrel at a point, O , a few millimeters above an eyepiece lens and just below the eye. An exterior source of light will be placed in the plane which contains O and is perpendicular to the microscope barrel. We fix a three-dimensional Cartesian coordinate system in space so that the Z -axis is coincident with the axis of the microscope barrel and the origin coincides with the pivot point of the glass. Let Z take values increasing upward. We then imagine a plane which is parallel with the glass surface. Letting $\bar{n}$ be the upward normal to the plane and $\bar{i}$, $\bar{j}$, $\bar{k}$ the unit vectors in the x , y , z directions respectively, we obtain a description of the

position of the glass through the usual spherical coordinates Θ and ϕ , where

$$\begin{aligned}\Theta &= \arccos (\bar{n} \cdot \bar{k}) \\ \phi &= \arctan \left(\frac{\bar{n} \cdot \bar{j}}{\bar{n} \cdot \bar{i}} \right)\end{aligned}$$

It follows that

$$\bar{n} = \bar{i} \sin \Theta \cos \phi + \bar{j} \sin \Theta \sin \phi + \bar{k} \cos \Theta$$

Allow the position vectors of the exterior light source and its virtual image to be given respectively by

$$\begin{aligned}\bar{L} &= (\bar{i}x_1 + \bar{j}y_1) \\ \bar{V} &= (\bar{i}x + \bar{j}y + \bar{k}z)\end{aligned}$$

From geometrical optics we get the equation

$$\bar{V} = \bar{L} - 2(\bar{n} \cdot \bar{L})\bar{n}$$

Finally by computing the components of $\bar{i}$, $\bar{j}$, and $\bar{k}$ we obtain the position of the virtual image in terms of Θ and ϕ . Taking $y_1 = 0$, as we may with no loss of generality, the result becomes

$$\begin{aligned}x &= x_1 \cos^2 \Theta - x_1 \sin^2 \Theta \cos \delta \\ y &= -x_1 \sin^2 \Theta \sin \delta \\ z &= -2x_1 \cos \Theta \sin \Theta \cos \frac{\delta}{2}, \quad \delta = 2\phi.\end{aligned}$$

Clearly if Θ is fixed and ϕ varies, the x, y motion of the image is a circle with center at $(x_1 \cos^2 \Theta, 0, 0)$ and of radius $x_1 \sin^2 \Theta$. Its angular motion is twice that of the glass strip. Setting $\Theta = 45^\circ$, we obtain

$$\begin{aligned}x &= \frac{x_1}{2} - \frac{x_1}{2} \cos \delta \\ y &= -\frac{x_1}{2} \sin \delta \\ z &= -x_1 \cos \frac{\delta}{2}\end{aligned}$$

If ϕ is small and x_1 is set equal to the focal distance, the light point will appear to move in the field of view.

Now let us compare its motion with that of the image P of a point on a reticle. The respective displacements, Δd and Δd_1 , for given $\Delta\phi$, will have the ratio

$$\frac{\Delta d}{\Delta d_1} = \frac{\text{focal distance}}{\text{power} \times \text{cell length}} \quad (1)$$

where the power is the power of the microscope optical system and the cell length is the virtual distance from the center of the field to the image P.

Interpreting our mathematical model in terms of a practical instrument, we see that a series of needle points centered at $(x_1, 0, 0)$ can be used to mark off angular units. In fact, they will compose a scale which moves across the field of view while a central reticle line sweeps out a given angle. Since the focal length of the microscope is about 25 cm, the scale is comparable to one swept by a 25 cm lever arm attached to the outside of an eye piece. By fixing the glass strip in a separate cylinder from that which holds the eye piece and reticle, the scale of needles can always be kept near the center of the field regardless of the orientation of the angle to be measured. They will not interfere with the normal operation of the microscope.

The usefulness of the instrument is greatest for small angles, though it will measure angles up to 20 degrees with ease. Its advantage, as compared with a method which reads reticles displacements, is obtained

from formula (1). For instance, if the power is 450x and the field of view has diameter $22^5\mu$, the maximum practical cell length is 100μ . In such a case, the advantage $=\Delta d/\Delta d_1 = 5.5$. The mechanical accuracy of the goniometer is determined solely by the bearings of the cylinders, because measurements can be made independent of the stage.

Two reflection goniometers were machined by W. M. Brower for the University of California Radiation Laboratory. One is shown in Figures 1 and 2. The cylinders, made of copper and designed to accommodate a Spencer 5LX microscope, provide a 1.33 inch bearing surface. The outside surface is coated with nickel. The glass strip is ordinary cover glass material. A slight wedging of the glass is advantageously used to give a sharp reflected image: The images from the two reflecting surfaces are made to coincide. In Figure 3 the goniometer is set up to measure small angles. The needles are placed against a black wall to avoid fading the field with extra light. They are tilted at an angle to reflect the light of the room with maximum intensity.

I wish to thank Dr. W. H. Barkas for the mathematical analysis of the device. I am grateful to Mr. H. Johnson and W. M. Brower for valuable suggestions about a practical design.

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1-21-52 gg

FIGURE CAPTIONS

Fig. 1 - Goniometer mounted on the microscope. The glass strip visible inside the cap reflects light from the opening in the cylinder wall. The upper and lower knurled-shoulders move the glass strip and ocular, respectively. An outside angular scale is unessential.

Fig. 2 - Exploded view of the instrument, the three cylinders and a protective cap. The cylinders telescope one another from right to left while the inner one clamps to the microscope barrel.

Fig. 3 - The goniometer set up to measure small angles. The needles, whose reflected image appears in the field of view, are placed against a black wall. Their separations correspond to one tenth of a degree and one degree units.

ZN177

Fig. 1

ZN176

Fig. 2

ZN 175

Fig. 3