A clean specimen surface is essential for successful low energy electron diffraction. In our experiments we used an emission microscope with ultrahigh vacuum in the specimen chamber². At a pressure of about 10^{-8} torr it was possible to obtain diffraction patterns from several different specimens after preliminary heating. A diffraction pattern from a silicon single crystal with the orientation (111) is shown in Fig. 2. Fig. 3 shows the diffraction pattern of mica taken at a temperature $\sim 400^\circ\text{C}$.

Energies up to about 300 eV are used for low energy electron diffraction and at about 2,000 eV Auger electron spectroscopy is also possible. The combination of emission microscopy, low energy electron diffraction and Auger spectroscopy in a single instrument can thus contribute significantly to a detailed examination of specimen properties.

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¹ Delong, A., and Drahoš, V., *Proc. Seventh Internat. Conf. Electron Microscopy*, 1, 197 (Grenoble, 1970).

² Delong, A., and Drahoš, V., *J. Phys. E.*, 1, 397 (1968).

Transformation to Rotating Coordinates, reply to Atwater

ATWATER¹ in his treatment of the transformation to rotating coordinates arbitrarily applied a simple Lorentz transformation to the periphery of a rotating disk having a symmetrical pattern and obtained, by using a constant radius, an asymmetrical pattern. He concluded that the special theory of relativity (STR) may not be applied to the problem of the rotating disk. I think that this conclusion may be unwarranted.

The equivalence principle, which locally equates an accelerated frame of reference with a gravitational field, has not only been a foundation of general relativity but has unfortunately also clouded the division between the domains of applicability of the special theory and the general theory of relativity. The STR is here taken in the sense of Bergmann²; that is it is extended to include non-inertial frames of reference which are covariantly characterized by their Riemann curvature tensor being zero. Acceptance of this point of view gives an unambiguous criterion for the applicability of the STR.

In terms of the non-inertial reference system fixed to the rotating disk, the metric may be written as

$$ds^2 = (c^2 - \omega^2 r^2) dt^2 - 2\omega r^2 d\phi dt - dz^2 - r^2 d\phi^2 - dr^2 \quad (1)$$

It is straightforward explicitly to show that the curvature tensor $R^{abcd} = 0$, as expected. The problem of the rotating disk is then in the domain of the STR, in spite of the non-Euclidean character of its spatial geometry.

It should be noted that rigorously it is not possible to apply a simple Lorentz transformation to the periphery of a rotating disk because the velocities at each point on the periphery are not collinear. (A series of non-collinear Lorentz transformations is of course equivalent to a simple Lorentz transformation plus a rotation, which is the origin of the well known Thomas precession.) Lorentz transformations are representable as rotations in Minkowski space, and the problem of composing non-collinear velocities is equivalent to that of spherical trigonometry on a sphere of radius i . A Lorentz transformation becomes a geodesic arc on the surface of the sphere. A cycle³ of Lorentz transformations applied to a spatial trihedron at the periphery of the rotating disk does not return the axes of the trihedron to their original orientations, but rotates them through an angle equal to the spherical excess of the geodesic

polygon corresponding to the cycle. The trihedral precesses with an angular velocity ω_T , where

$$\omega_T = [(1 - \omega^2 r^2 / c^2)^{-1} - 1] \omega \quad (2)$$

and this is directed parallel to the angular velocity of the disk.

To ascertain what a material rotating disk actually looks like with respect to an inertial frame of reference we must examine not only these kinematical considerations, but also questions of elasticity and dynamics^{4,5}.

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¹ Atwater, H. A., *Nature*, **228**, 272 (1970).

² Bergmann, P., *Handbuch der Physik* (Springer, Berlin, 1962).

³ Lalan, V., *CR Acad. Sci.*, **236**, 2297 (1953); Garnier, R., *CR Acad. Sci.*, **236**, 2299 (1953).

⁴ Eddington, A. S., *The Mathematical Theory of Relativity* (Cambridge, New York, 1960).

⁵ Clark, G. L., *Proc. Roy. Soc. Edin.*, A, **62**, 434 (1947).

ATWATER's treatment of the rotating disk in special relativity¹ is open to question. If a ring made of a physical material, such as a circular wire, initially stationary, is made to rotate without changing its radius, the wire will stretch. In Atwater's example, the painted strips will remain of the same size. He apparently does not appreciate that a stress of tension is introduced into the disk. If the material were to crack under the stress, it would be possible for the painted strips to appear as he suggests².

Of more fundamental importance, however, is the failure of many (including, apparently, Atwater) to realize that special relativity is perfectly applicable to all problems which do not involve gravitation. The fact that a coordinate system fixed in the rotating disk is not an inertial frame does not eliminate the existence of an inertial frame, and in this frame the metric is Minkowski. As long as the transformation equations between one frame, whether rotating or accelerating, and an inertial frame are known special relativity can always be used, although as Atwater points out, the metric may not be in its familiar Minkowski form.

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¹ Atwater, H. A., *Nature*, **228**, 272 (1970).

² Robertson, H. P., and Noonan, T. W., *Relativity and Cosmology* (Saunders, Philadelphia, 1968).

PROFESSOR ATWATER writes: In reply to Noonan's comments concerning the metric of rotating systems¹, it is clear that the metric of such systems is not Minkowski. Because the components of the Minkowski tensor are constants, the resulting Christoffel symbol $\frac{1}{2} g^{ja}(g_{ia,k} + g_{ka,i} - g_{ik,a})$ vanishes, and the equation for the geodesic lines is $d^2 x^j / ds^2 = 0$ (see ref. 2). In a Minkowski frame therefore free particles will move along straight lines. Free particles do not move on straight-line paths in a rotating frame, but follow curved-line paths under the influence of the apparent forces called centrifugal and Coriolis forces. Similarly, photons will travel on curvilinear paths in a rotating frame³. We do not know with certainty how to transform to rotating coordinates¹.

It would be interesting to see Noonan's statements concerning the rotating disk. It would be preferable to have laws of space-time physics which do not depend on the elastic properties of particular materials. The textbook discussion to which he refers² provides only assertions concerning the peripheral measure in the rotating system, leaving open the questions of radial, time, and angle transformation. The discussion is based on special relativity, and therefore cannot yield any conclusive information concerning the coordinates of a non-inertial frame.