New Photographic Emulsions Showing Improved Tracks of Ionizing Particles

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THE tracks of protons and of heavier particles can be recorded in photographic emulsions. In Eastman α emulsion, the tracks show up as rows of grains about 0.8μ in diameter, the distance between the centers of consecutive grains being about $1.5–2\mu$ for an α-particle or a proton near the end of its range, and larger for a fast proton.

New emulsions have been prepared, in which the grains, as seen under the microscope after development, appear to have a diameter of 0.2μ or smaller, and in which the distance between the centers of consecutive grains may have the following small values: $0.1–0.2\mu$ at the beginning of the tracks of a heavy fission fragment; $0.2–0.3\mu$ for an α-particle or at the end of a proton track; 0.5μ at the beginning of a 7–8 Mev proton track. The stopping power is about 1800.

A typical emulsion was prepared by the simultaneous dropwise addition of 30 cc of a 0.6-g/cc solution of silver nitrate, and of 30 cc of an equivalent solution of potassium bromide, to 75 cc of a well-stirred 6 percent gelatine solution kept at 40–50°C. During the operation, the volumes of the two reacting solutions which have been poured are kept constantly equal. The operation lasts 30 minutes. This gives a concentrated emulsion similar to the Lippmann type, which contains after washing and drying, about 80 percent of silver bromide in the form of grains less than 0.2μ diameter. Concentrations as high as 92 to 95 percent can be obtained directly by a like procedure. Slightly larger grains result from operating a room temperature or from slower stirring. A mixture of halides can be used. Grains are finer, and silver bromide concentration is higher than in most commercial emulsions.

A smaller grain size, a lower silver bromide concentration, and a weaker development will tend to render visible exclusively the tracks of heavy fission fragments; by controlling these factors, it is possible to bring out the α-rays too, or to bring out the protons as well.

Complete fission tracks show clearly the ionization maximum at the center, and in certain emulsions the maximum at the very end of the tracks too. Range measurements of ThC′ α-particles in one case indicated a standard deviation of 2 percent, which is about three times that obtained in air, and half that obtained in an Eastman α-emulsion. Proton tracks of a few 100 kev can be clearly recognized, as the end of a proton track may show as many as 2 or 3 grains per mm of air equivalent; the beginning of the long proton tracks is also very clear; the beginning of a 7–8 Mev proton may show 1 grain per mm of air equivalent, in which case each developed grain corresponds to an energy loss of 5 kev.

Such a high sensitivity leads one to believe that electrons in the equivalent of their last few centimeters of air render developable grains spaced in the emulsion by only a few millimeters of air equivalent, but no unquestionable tracks of electrons have yet been seen. Mesotrons near the end of their path should leave visible tracks.

β- and γ-rays will fog these plates; but proton tracks have been seen on a plate fogged by 100 r units of γ-rays, and fission tracks on a plate fogged by several hundred r units of γ-rays.

These emulsions are not very sensitive to visible light, but their small gelatine contents may render them of some use in the Schumann region. A chromic acid treatment, as is well known, removes from the silver bromide grains the sensitivity specks which enhance the sensitivity of the grains toward light. Such a treatment was observed to decrease or to remove the sensitivity to the tracks. It therefore appears that the sensitivity specks that enhance the sensitivity to light also enhance the sensitivity to the tracks.

A more complete report will be sent to the *Canadian Journal of Research.*

This work was carried on between June and December, 1945.

The Advance of the Perihelion of Mercury

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ANY action of one body on another after the finite time required for propagation from the first body to the second body has more concrete physical meaning than an assumed instantaneous action at a distance, since the latter does not conform to any known method such as wave motion or ballistic transfer. Transfer at finite speed can occur by means of wave motion or be ballistic even when it may not yet be known which of these modes of propagation is the proper one.

In the development of the reciprocal energy and force formulas of one charge on another,[1] magnetic force is considered as the variation in electrostatic force due to the ratio of the (relative) velocity of the charges to the propagation speed c. Gravitational attraction of one atom on another is very much smaller than their magnetic forces, and as has been suggested may very well be caused by further modification of electromagnetic forces. Such an explanation would be entirely in keeping with the mass-energy relation obtained from the coefficient of the acceleration term in the reciprocal force formula. The question at once arises, that if mass is a measure of internal electrostatic energy, why not also a function of internal magnetic energy. These two suggested developments point to higher power terms in the $1/c$ expansion. Coupled with the finite propagation discussed above, it should not be surprising that gravitational force be found to follow the reciprocal formula, reducing to Newton's gravitational law for small velocities.

The theories of Ampère, Weber, and Riemann went a long way in the direction of a pure relativistic description of nature. They were not carried far enough, however, to describe adequately the transverse propagation of light. Also, the best value in 1890 for the advance of the perihelion of mercury, 38″ per century, gave approximately

$\alpha=5/3$ in the combination of the Weber and Riemann formulas in the hands of Tisserand[2] and Lévy,[3] $W=\alpha W_R+(1-\alpha)W_W$. The Ritz[4] theory and O'Rahilly's[5] preference $\lambda=3$ ($=4A-1$, corresponding to $A=1$ in the reciprocal force) failed to account for Mercury's advance because of the lack of certain acceleration terms. The reciprocal energy formula,[1] however, with the preferred value $A=1$ (and hence with $B=-\frac{1}{2}$), namely

$$W=(ee'/r)(1+u^2/c^2-(\mathbf{u}\cdot\mathbf{r})^2/2c^2r^2+\cdots), \quad (1)$$

when applied to gravitation, predicts closely the advance of the perihelion of mercury. Using the value 14.4″ per century given by Tisserand for the Weber formula[2] and twice that for the Riemann energy,[3] and setting $\alpha=2$, which reduces Lévy's expression to Eq. (1), one finds for the advance of the perihelion of Mercury the value 43.2″ per century. The observational advance[6] is listed as 43.5″ per century, while the value predicted by the partially relativistic theory of Einstein is given as 42.9″ per century. A recheck using more recent values of the measured quantities gives the advance of the perihelion of Mercury as 43.0″ per century, both on the standard relativity basis and on the basis of the reciprocal force formula. The observed advance of the perihelion of the planets thus does not distinguish between Einstein relativity and an electrical theory conforming the Newtonian relativity.

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[3] M. Lévy, Comptes rendus **110**, 545 (1890).
[4] W. Ritz, Ann. de Chemie et de Physique **13**, 145 ff (1908). Ges. Werke-Œuvres, p. 421.
[5] Alfred O'Rahilly, *Electromagnetics*, pp. 588, 616, 544.
[6] R. C. Tolman, *Relativity, Thermodynamics and Cosmology*, p. 209.

Energy-Angle Distribution of Betatron Target Radiation†

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An approximate expression for the energy-angle distribution of the bremsstrahlung produced by fast electrons in a thin target has been given by Sommerfeld.[1] This is obtained by integration of the Bethe-Heitler formula over the angular coordinates of the outgoing electron, and is valid with neglect of screening when the energy of the incident electron is large in comparison with its rest energy. It is not applicable when the target is of the thickness used in betatrons, since the electron beam is spread out by multiple scattering in the target.

According to Williams[2] the normalized distribution in angle θ per unit solid angle of electrons of energy E after penetrating a thickness t of target containing N atoms of nuclear charge Ze per unit volume is:

$$(1/2\pi\theta_0^2)\exp(-\theta^2/2\theta_0^2), \quad \theta_0=(9.2Ze^2/E)(Nt)^{\frac{1}{2}}\equiv(\beta t)^{\frac{1}{2}};$$

the numerical coefficient 9.2 is nearly constant for heavy metal targets such as tungsten having thicknesses of the order of a tenth millimeter. The angular spread of the x-rays due to just the radiation process is of order mc^2/E. For tungsten, θ_0 is large compared to mc^2/E if $t\gg10^{-4}$ cm; this is usually the case.

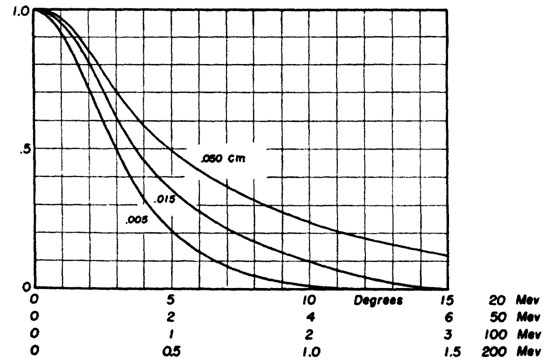

FIG. 1. Ratio of radiation intensity at angle θ to the intensity at $\theta=0$ for three thicknesses of tungsten target.

Since electrons are radiating at all values of t from zero to the total target thickness x, Williams' formula must be integrated over t to give the effective electron angular distribution per unit solid angle:

$$(1/2\pi\beta)[-Ei(-\theta^2/2\beta x)].$$

This assumes single traversal of the target, and is valid so long as the target is thin enough so that there is not excessive straggling of the electrons; for tungsten this corresponds to $x\gtrsim0.05$ cm. The energy-angle distribution of the x-rays is now obtained by combining this electron distribution with Sommerfeld's formula. For angles somewhat larger than mc^2/E this means simply that the angular distribution of the x-rays is the same as that of the electrons, and the energy spectrum is that obtained by integrating the Bethe-Heitler formula over the directions of both the outgoing electron and the quantum.[3] For small angles, however, the divergence in the electron distribution makes it necessary to carry through the combination in detail. This is readily done for $\theta=0$; in the absence of screening, the energy distribution is still the integrated spectrum, and this is a good approximation when screening is included.

The result is that to good approximation the energy distribution at all angles is that usually associated with the total radiation. The ratio of intensity at an angle θ somewhat larger than mc^2/E to the intensity at $\theta=0$ is per unit solid angle:

$$[-Ei(-\theta^2/2\beta x)]/[\ln(2\beta xE^2/m^2c^4)-0.5772].$$

Since β is proportional to $1/E^2$, the denominator is independent of E and curves for different energies differ only by a scale factor that is inversely proportional to E. Curves for three thicknesses of tungsten target are shown in Fig. 1; they are in good agreement with measurements reported by D. W. Kerst (private communication). Thanks are due T/5 C. B. Gass for help with the numerical computations.

* Now returned to the University of Pennsylvania from leave of absence.
† Submitted for clearance March 19, 1946.

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