in Mev $gm^{-1}cm^2$, then the rate of energy loss U, in the mixture of these stopping materials is: $U = C_eU_e + C_hU_h + C_wU_w$. It is remarked that C_h, for example, may be negative. The range, $R(gm/cm^2)$, for any composition then can be calculated from:

$$R(T_0) = \int_0^{T_0} \frac{dT}{U} \tag{10.7.1}$$

Because the range-velocity curves have similar shapes for most materials we can obtain the range with negligible error in another way that is much simpler. Suppose the mean range is $R(gm/cm^2)$ for a homogeneous mixture or compound of n different materials in which the ranges for the same energy in the different constituents are R_1, R_2, R_3, $\cdots$, R_i, $\cdots$, R_n. Then R can be found without integration from:

$$1/R = \sum_{i=1}^{u} \frac{C_i}{R_i} \tag{10.7.2}$$

Here C_i is the fraction by weight of the ith constituent in the stopping material.

We may choose to regard the fluctuations of emulsion composition as varying the concentrations of normal emulsion, silver bromide, and water. For the case of these three components, taken in that order, we obtain R_1 from Table 10.4.1, R_2 from Table 10.7.1, and R_3 from Table 10.7.2. In this way one can obtain without integration the range-energy relations for all usual emulsion compositions in terms of the range-energy relations of its components.

10.8 Range Straggling in Emulsion

When a group of identical particles all of the same energy produce tracks in emulsion, the lengths of the tracks will not all be the same. The reasons for and the magnitude of this effect we shall now investigate, considering first the most important phenomenon, electron-collision straggling.

According to Eq. (9.1.1), in unit path a particle of charge ze and velocity βc transmits energy between w and $w + dw$ to an average number of electrons equal to:

$$\frac{2\pi n z^2 r_0^2 mc^2}{\beta^2} \left(1 - \frac{\beta^2 w}{w_{\max}}\right) \frac{dw}{w^2} \tag{10.8.1}$$

where n is the electron density. The mean-square energy transfer in path ΔR then is

$$\langle(\Delta T)^2\rangle = \frac{2\pi n z^2 r_0^2 mc^2}{\beta^2}\Delta R\left[(w_{\max} - \epsilon) - \frac{\beta^2}{2w_{\max}}(w_{\max}^2 - \epsilon^2)\right] \quad (10.8.2)$$

where ϵ is an effective lower limit to the energy transfer, and $w_{\max} \approx 2mc^2\beta^2\gamma^2$.

The mean energy transfer $\langle\Delta T\rangle$ in path ΔR is

$$\langle\Delta T\rangle \approx \frac{4\pi n z^2 r_0^2 mc^2}{\beta^2}\Delta R\left[\ln\frac{w_{\max}}{I} - \beta^2\right]$$

The increase of the energy straggling, $(d/dR)(\sigma_T^2)$, per unit path is

$$\lim_{\Delta R\to 0}\frac{\langle(\Delta T)^2\rangle - \langle\Delta T\rangle^2}{\Delta R}.$$

When $\beta \to 1$, $\langle\Delta T\rangle^2/\langle(\Delta T)^2\rangle$ and $\epsilon/w_{\max}$ approach zero, so that

$$\frac{d}{dR}(\sigma_T^2) = 4\pi n z^2 r_0^2 m^2 c^4\left[\frac{1-\beta^2/2}{1-\beta^2}\right] \quad (10.8.3)$$

Now the equation $\Delta\sigma_T^2 = (dT/dR)^2\,\Delta\sigma_R^2$ connects an increment of energy straggling with an increment, $\Delta\sigma_R^2$, of range straggling. Therefore, for high-energy particles the variance of the range is

$$\sigma_R^2(R_1) = 4\pi n z^2 r_0^2 m^2 c^4\int_0^{R_1}\frac{dR}{\mathscr{I}^2}\frac{(1-\beta^2/2)}{(1-\beta^2)} \quad (10.8.4)$$

This can also be written

$$\sigma_R^2 = 4\pi n z^2 r_0^2 m^2 c^4\int_0^{T_0}\frac{dT}{\mathscr{I}^3}\frac{(1-\beta^2/2)}{(1-\beta^2)} \quad (10.8.5)$$

where T_0 is the particle kinetic energy.

This form was first given by Lindhard and Scharff (LS 53). It reduces at low velocities to the Bohr formula (B 15);

$$\sigma_R^2 = 4\pi n z^2 r_0^2 m^2 c^4\int_0^{T_0}\frac{dT}{\mathscr{I}^3} \quad (10.8.6)$$

Sternheimer (S 60) does not approximate so drastically, and leaves the range variance in the form

$$\sigma_R^2 = 4\pi n z^2 r_0^2 m^2 c^4\int_0^{T_0}\frac{K\,dT(1-\beta^2/2)}{\mathscr{I}^3(1-\beta^2)(1+(2m/\mu)\gamma)} \quad (10.8.7)$$

The factor K takes into account the effect of binding of the atomic electrons, which we merely symbolized by ϵ. At low velocities K is significantly greater than unity, and it increases slowly with the atomic number of the stopping material. The reason for this is not hard to understand. Small energy transfers to a heavy atom are improbable because in such an atom most of the electrons are firmly bound. Consequently the particles typically are brought to rest in a heavy element by large energy transfers rather than by a greater number of small ones. Bethe's (LB 37) formula for K is

$$K = \frac{Z_{eff}}{Z} + \sum_n \frac{k_n I_n Z_n}{mv^2} \ln \frac{2mv^2}{I_n} \tag{10.8.8}$$

Here Z_n is the number of electrons in the nth shell of the atom, I_n is the effective excitation potential of these electrons, k_n is a constant which was estimated to be 4/3. The summation is extended over the shells for which $I_n < 2mv^2$. The quantity Z_{eff} is the number of electrons in the shells over which the summation extends.

Sternheimer leaves the factor $1 + (2m/\mu)\gamma$ in the denominator (m/μ is the electron/beam-particle mass-ratio) to better approximate the maximum energy transfer, Eq. (9.1.2). It is questionable, however, whether the formula yet is really applicable at extremely high energies. The electromagnetic form factor of the beam particle also affects the electron scattering cross section for large energy transfers, and this has not been included in the calculation.

Using the simpler form, Eq. (10.8.5), we see that

$$\frac{z^4\sigma_R^2}{M} = 4\pi r_0^2 m^2 c^4 \int_0^{\beta_0} \frac{(1-\beta^2/2)\,\beta\, d\beta}{\iota^3(1-\beta^2)^{5/2}}$$

is a function of velocity $\beta_0 c$, alone.

On the other hand, z^2R/M also is solely a function of β_0. Then

$$\frac{z^4\sigma_R^2}{M} \Big/ \frac{z^4R^2}{M^2} = M(\sigma_R/R)^2$$

is a function of the velocity (BSB 55). Its value can be calculated for a proton. The results are then applicable to other particles of the same velocity. In Table 10.8.1, the quantity $100M^{1/2}\sigma_R/R$ is given with reasonable accuracy although all the theoretical refinements mentioned above have not been included. Most are not justified for emulsion. The percentage range straggling, $100\sigma_R/R$, increases slowly with the atomic number of the absorber, and is also a slowly varying function of the particle velocity.

TABLE 10.8.1

PERCENTAGE STRAGGLING OF PROTON RANGES IN EMULSION CAUSED BY ELECTRON COLLISIONS

τ (Mev)	$(100\ M^{1/2}\sigma_R/R)$
1	2.11
2	1.94
5	1.66
10	1.53
20	1.42
50	1.29
100	1.21
200	1.13
500	1.02
1000	0.95
2000	0.90
5000	0.96
10,000	1.11

At high velocities electron-collision straggling dominates in the observed heavy-particle range distributions. At low velocities other effects are also important. It was found in a study (BSB 55) of the various straggling effects in emulsion that they could be classified as follows:

1. The Bohr straggling or electron-collision straggling evaluated above.

2. Straggling caused by macroscopic emulsion distortion. This was studied in Section 6.12.

3. Proportional straggling; that is, straggling for which the range variance is proportional to the range. This is of at least three types.

a. The observer error (excluding gross errors) is of this sort. It contributes a term, σ_0^2, to the net variance. Its magnitude is perhaps $0.01R(\mu)^2$.

b. Microscopic distortion straggling. It is argued that the dissolution of the silver halide crystals leaves cavities in the emulsion. The collapse of these cavities on drying is expected to lead to microscopic displacements of developed grains in random directions. This has a net effect on the track length. The variance, σ_b^2, of the track length introduced by this effect was estimated to be $\sigma_b^2 = [3(S_0 - 1)/20S_0]\langle D\rangle R$, where S_0 is the shrinkage factor.

c. Heterogeneity straggling treated below.

4. End straggling caused by the finite grain size and limited grain sensitivity. The standard deviation of the range for this reason varies from about $\langle D\rangle/2$ for saturated tracks to perhaps $1/g$ for very unsaturated tracks. It is important only for very short tracks.

5. Momentum straggling. Although this is not a true straggling effect, particle beams are never truly monoenergetic, and any energy dispersion of the beam will cause range dispersion which must be identified and separated from the true straggling effects.

The effect of heterogeneity is manifested when the particle is caused to traverse a composite material made up of materials of different stopping powers. The ratio of two such materials in equal segments of path is assumed to fluctuate in a random way. The effect has been calculated for emulsion as follows (B 59.1).

Let $\mathscr{I}_h$ and $\mathscr{I}_g$ be the mean energy losses in unit path when the particle traverses halide and gel, respectively. If the sum of the halide paths in a total path length μ is h, then the mean energy loss, η, in the path μ is: $\eta = \mu\mathscr{I}_h + (\mu - h)\mathscr{I}_g$.

We wish to calculate the straggling *additional* to the Bohr straggling so that $\mathscr{I}_h$ and $\mathscr{I}_g$ are considered constant rates of energy loss. Then the heterogeneity variance, σ_η^2, of the energy loss in path μ is $(\mathscr{I}_h - \mathscr{I}_g)^2\sigma_h^2$, σ_h^2 being the variance of h in path μ. The mean value of h in path μ is equal to $C\mu$ where C is the volume concentration of the halide.

Now using Eq. (3.9.24)

$$\sigma_h^2 = \pi N\left[\frac{\langle D^4\rangle}{8} - \frac{\langle D^3\rangle^2}{9\langle D^2\rangle}\right]\mu$$

so that

$$\sigma_h^2 = \pi N(\mathscr{I}_h - \mathscr{I}_g)^2\left[\frac{\langle D^4\rangle}{8} - \frac{\langle D^3\rangle^2}{9\langle D^2\rangle}\right]\mu$$

Let σ_T^2 be the variance of the residual energy of a particle from an originally monoenergetic population. Then σ_R^2, the variance of its residual range, is related to σ_T^2 by $d(\sigma_T^2) = \mathscr{I}^2 d(\sigma_R^2)$, when $\mathscr{I} = (\mathscr{I}_h - \mathscr{I}_g)C + \mathscr{I}_g$ is the mean space rate of energy loss. Then

$$\sigma_R^2 = \pi N\left[\frac{\langle D^4\rangle}{8} - \frac{\langle D^3\rangle^2}{9\langle D^2\rangle}\right]\int_0^{(R)}\left(\frac{\mathscr{I}_h - \mathscr{I}_g}{\mathscr{I}}\right)^2 dR \qquad (10.8.9)$$

We write

$$\gamma = \frac{\mathscr{I}_h - \mathscr{I}_g}{\mathscr{I}} = \frac{\mathscr{I}_h - \mathscr{I}}{(1 - C)\mathscr{I}}$$

The ratio, γ, is nearly constant at low velocities. It has a value of approximately 0.93 for a proton of 3-10 Mev in standard emulsion.

Now, if in addition the grain-diameter variance is not large:

$$\frac{\langle D^4\rangle}{8} - \frac{\langle D^3\rangle^2}{9\langle D^2\rangle} \approx \frac{\langle D^4\rangle}{72}\left(1 + \frac{8\sigma^2}{\langle D\rangle^2}\right)$$

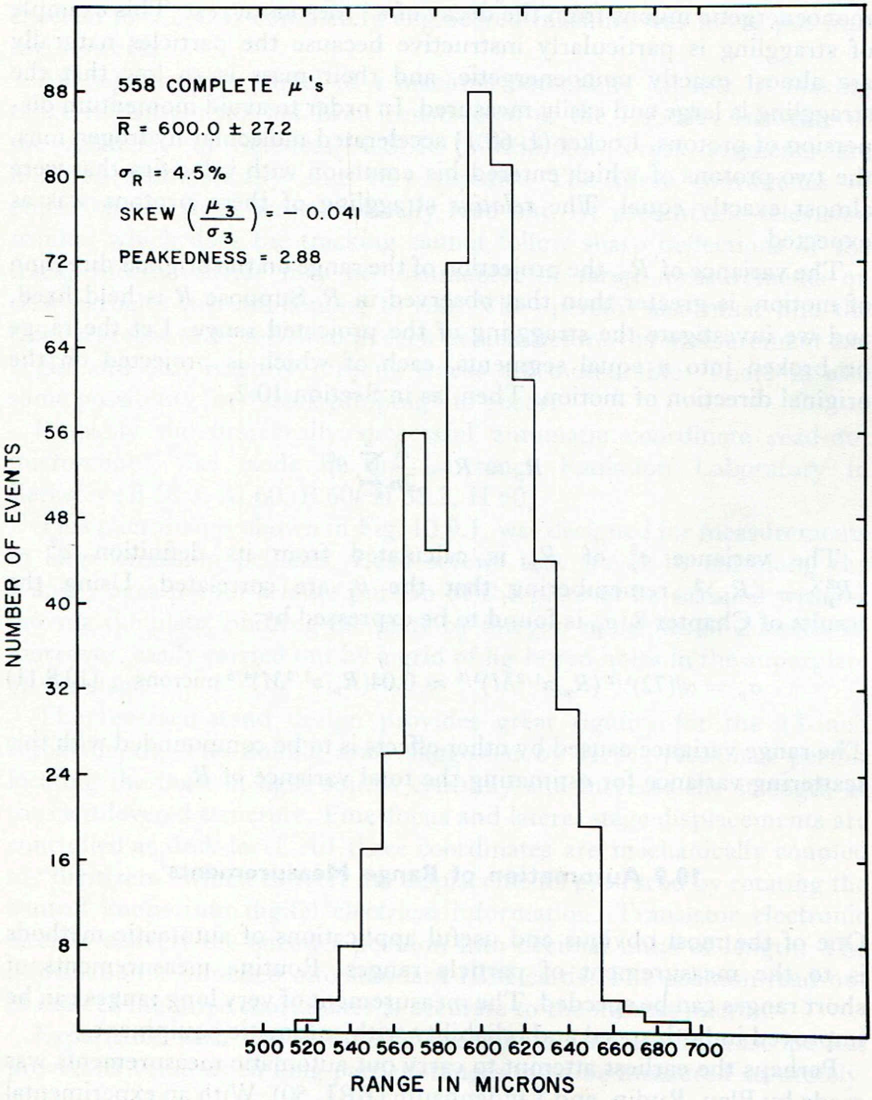

FIG. 10.8.1. Measured ranges of muons from π-μ decay in emulsion of standard composition (IDLRL).

so that

$$\sigma_R^2 \approx \frac{0.035 \langle D^{10} \rangle R}{\langle D^9 \rangle} \tag{10.8.10}$$

In Fig. 10.8.1, is shown the distribution of ranges observed for monoenergetic muons from the decay of π^+ mesons at rest. This example of straggling is particularly instructive because the particles naturally are almost exactly monoenergetic, and their mass is so low that the straggling is large and easily measured. In order to avoid momentum dispersion of protons, Locker (L 60.1) accelerated molecular hydrogen ions, the two protons of which entered his emulsion with velocities that were almost exactly equal. The *relative* straggling of these protons was as expected.

The variance of R_p, the projection of the range on the original direction of motion, is greater than that observed in R. Suppose R is held fixed, and we investigate the straggling of the projected range. Let the range be broken into n equal segments, each of which is projected on the original direction of motion. Then, as in Section 10.2,

$$R_p \approx R - \frac{R}{2n} \sum_{i=1}^{n} \theta_i^2$$

The variance σ_p^2 of R_p is calculated from its definition $\sigma_p^2 = \langle R_p^2 \rangle - \langle R_p \rangle^2$, remembering that the θ_i are correlated. Using the results of Chapter 8, σ_p is found to be expressed by:

$$\sigma_p = \alpha/(72)^{1/2} (R_p/z^{1/2}M)^{4/5} \approx 0.04(R_p/z^{1/2}M)^{4/5} \text{ microns} \tag{10.8.11}$$

The range variance caused by other effects is to be compounded with this scattering variance for estimating the total variance of R_p.

10.9 Automation of Range Measurements

One of the most obvious and useful applications of automatic methods is to the measurement of particle ranges. Routine measurements of short ranges can be speeded. The measurement of very long ranges can be improved in both speed and reliability with automatic equipment.

Perhaps the earliest attempt to carry out automatic measurements was made by Blau, Rudin, and Lindenbaum (BRL 50). With an experimental model they were able to perform simultaneously the functions of range measurements, track photometry, and track orientation measurements.

For the range measurement, selsyn motors drove the stage simultaneously along the x and y axes. The displacements were indicated on mechanical counters which could be photographed at points along the track. From this record the track geometry could be reconstructed and the range obtained. Repeated setting on a grain gave coordinate read-outs that checked to 0.2 μ. A completely engineered machine was never put into use, however.

An experimental model of a machine potentially capable of making range measurements has been constructed at the Lebedev Institute of the Academy of Sciences, USSR (VMSS 60). Track segments are followed automatically and very rapidly. The three coordinates of points on the track are periodically read out. At present the television scanner which does the tracking cannot follow sharp deflections of the track, and the device may be unsuitable for range measurements on slow particles that are coming to rest. The operator also must find the track segment to be followed in each pellicle before the measurement can begin and only slightly dipping tracks are measurable. There is also some possibility for "track jumping" to occur.

Probably the first really successful automatic coordinate read-out microscope* was made in the Lawrence Radiation Laboratory in Berkeley (B 58.2, M 60, B 60, H 58.2, H 60).

This microscope, shown in Fig. 10.9.1, was designed for measurements in large emulsion pellicles. Lead screws that travel 10 cm along the x and y axes permit a large portion of the plate to be scanned without moving the plate. Shifting the plate by integral multiples of 2 inches is, moreover, easily carried out by a grid of jig-bored holes in the superplate on the stage.

The reversed-stand design provides great rigidity for the 13-inch throat depth. The double arms suggested by H. H. Heckman permit locating the built-in light source centrally and increase the strength of the cantilevered structure. Fine-focus and lateral stage displacements are controlled at desk-level. All three coordinates are mechanically coupled to "digitizers" which convert the displacements produced by rotating the control knobs into digital electrical information. Transistor electronic circuits convert the encoder position into decimal units of length. The information is punched into standard IBM cards. The position read-out of each of the three coordinates is accurate to the nearest micron.

Experience with this automatic coordinate read-out microscope has proved its value when long particle ranges must be measured accurately.

* Chief among those responsible for this instrument were: Dr. Conrad Mason, James C. Hodges, T. G. Taussig, and J. A. Russell.

Measurement programs which included measurement of the Λ-hyperon mass, measurement of the ranges of protons and π^+ mesons from the decay of Σ^+ hyperons, and measurements of the particle ranges from the reaction $K^- + p \rightarrow \Sigma^{\pm} + \pi^{\mp}$ have been carried out successfully. Each range was measured at least twice to eliminate human errors. The availability of the automatic equipment in some instances permitted

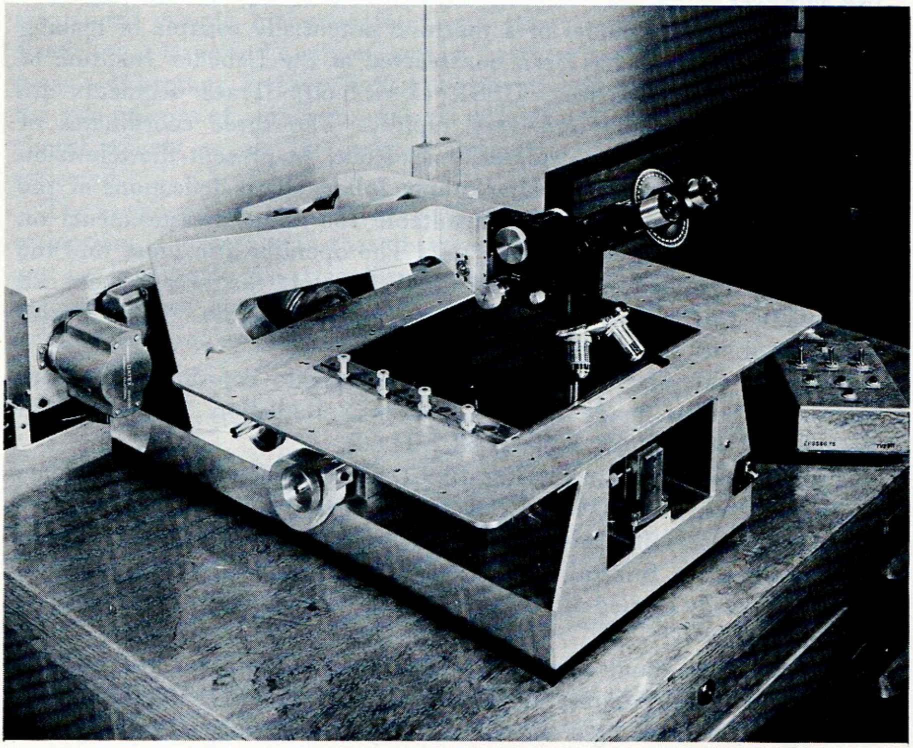

FIG. 10.9:1. Microscope for automatic range measurements (IDLRL).

tasks to be undertaken that otherwise would have been regarded as too difficult.

Another microscope with three-coordinate read-out was built at the Lawrence Radiation Laboratory in Berkeley at the instigation of Richard Lehman. It is designed specifically for neutron spectroscopy, and for this purpose it has been very successful.

At the Livermore Branch of the Lawrence Radiation Laboratory Dr. R. S. White developed digitized read-out equipment for each scanning microscope, thus multiplying the effectiveness of the scanner for certain tasks. The output of each microscope is recorded on tape. This is subsequently run through high-speed IBM computing equipment and the desired quantities calculated by the appropriate programs. The technical details of this system have been described in a Datex Corporation Instruction Manual (DC 59). The microscope is shown in Fig. 10.9.2.

FIG. 10.9.2. Digitized Livermore scanning microscope and associated equipment. An enlarged section of the grid is helpful in plotting the paths of particles through emulsion pellicles. (Courtesy of R. S. White.)

10.10 Ranges of Very Slow Particles

It makes a difference in its subsequent reaction behavior whether a negative particle stops in a silver bromide crystal or in gel. In the first instance it will almost surely be captured by a heavy nucleus. In an environment of light nuclei, however, if it is captured the particle, of course will react with a light nucleus. When the particle is weakly interacting, decay also can compete with capture. The crystal size, the concentration of silver halide, and the particle mass each affect the fraction captured in the light elements. The proportion depends somewhat on the crystal size and on the particle mass, because at low velocities the stopping power of a light element increases relative to that of a heavy element as the velocity decreases. At exceedingly low velocities the range (in microns) is about the same in gel as in silver bromide.

The relative capture probabilities have been calculated by Hill (H 61). He finds the ratio of capture in halide to capture in gel to be 1.69 and 1.67 for K^- mesons, and 1.52 and 1.54 for negative muons in G.5 and K.5 emulsion, respectively. These results are in accord with existing observations (PSMT 61, P 49.1, C-P 49, F 51).

Positive-particle behavior at very low velocities is not well known. After such a particle is neutralized by electron capture it may migrate a short distance, but efforts to detect this migration distance for pions and muons have not been successful. Positronium, muonium, pionium, kaonium, hyperonium, etc., are hydrogen-like atoms with positrons, muons, etc., as nuclei.

A particle range of a micron or so in emulsion is rather useless for energy determination or for identification of a particle. Occasionally knowledge of such a range may be needed, however, for a special purpose, as, for example, to estimate whether a nucleus recoiling in the gel is likely to penetrate a crystal.

In some cases ranges of low-velocity heavy fragments have been measured in air. Such ranges can be converted to emulsion ranges with only moderate uncertainty if one uses the low-energy integral stopping power of emulsion. This stopping power is given in Table 10.3.1 as 1285. Ranges of heavy fragments in a number of metal foils have been measured by Winsberg and Alexander (WA 60). These may also be used to estimate emulsion ranges.

Because a positively charged nucleus at low velocity is neutralized by the capture of electrons, and nonionizing stopping processes tend to become important, one may question whether the visible end of the track in emulsion actually defines the point where the atom came to rest. This question was studied by Sevier (S 61) and a definite answer was obtained. In Fig. 10.10.1 is shown a photomicrograph in K.5 emulsion of the track of a fission fragment, and the electrons emitted from the fission product. It was found by careful analysis of the points of origin of the electrons that the last grain in K.5 emulsion extended an average distance of $0.13 \pm 0.05\,\mu$ beyond the point where the atom came to rest. This is in fair accord with our assumption that the track terminus should be taken near the center of the last grain.

The range of an ion with energy in the Kev region, as a theoretical problem, has been treated recently by Lindhard and Scharff (LS 61).

They find that in first approximation the average range is proportional to the energy.

Particle ranges in emulsion are meaningless in the energy interval where these formulas are valid. However, ranges of slow, heavy ions in other materials have recently been measured by Powers and Whaling (PW 61) to check the formula of Lindhard and Scharff in the 50-500 Kev

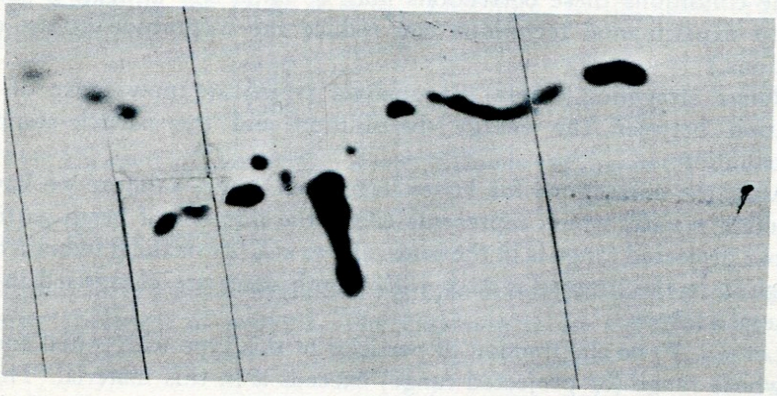

FIG. 10.10.1. Photomicrograph of track of fission fragment from the terminus of which electron tracks originate. (Photomicrograph by C. Cole.)

region. They used ions in the atomic number interval 7 to 54, and absorbers of Be, B, C, and Al. They found the linear range-energy relation to be valid for A, Kr, and Xe ions, but the rate of energy loss increased with ion energy for N and Ne ions. Their ranges came out about 20% lower than the estimates of Lindhard and Scharff, but by adding an electronic component of stopping they were able to bring the theory into agreement with the measurements.

Therefore, it would appear that their formulas might be applied to emulsion to answer questions about the behavior of specific particles at very low velocities. One result of their work is the conclusion that the straggling is comparable with the range itself. Also, the true range is considerably greater than the projected range.

10.11 Range Spectra

10.11.1 Homogeneous Absorber

If a beam of particles is incident normally on a plane surface of a homogeneous absorber, such as an emulsion stack, it is possible to obtain the energy distribution of the beam by several methods. It can be obtained, for example, by multiple scattering and/or ionization measurements on the tracks that enter the stack. These measurements are discussed in Chapters 8 and 9. It may also be found if the particles are brought to rest in the absorber. (Corrections must be made for those that interact in flight or escape without being brought to rest. Under some conditions these corrections may be large and difficult to make. Good experimantal technique can reduce the magnitude of the corrections.)

Range straggling enters the analysis which we now make of the relation between the energy distribution and the particle-stopping distribution.

After the corrections for losses have been made, suppose we have a function $n(x)dx$, which represents either the number of beam particles whose projected range is in the interval x to $x + dx$ or the number whose range is in the interval x to $x + dx$—both cases are comprised in the general analysis.

Let $g(x, T)$ be the fraction of particles of this type with initial energy T whose range (or projected range) exceeds x in this material. This is obtained from the range-straggling curve or from the projected-range straggling curve. Let $f(T)$ be the function we wish to determine. The integral $\int_T^\infty f(T)dT$ is the number of particles in the beam whose initial energy exceeded T.

Then the number of particles stopping between x and $x + dx$ is

$$n(x)\, dx = -\, dx \int_{T=0}^{\infty} f(T) \frac{\partial g}{\partial x}\, dT \qquad (10.11.1)$$

This expression does not immediately yield $f(T)$, especially when the range straggling is not small compared to the range. However, one method that is always available for finding $f(T)$ is to guess its form and carry out the integration. Then one can correct $f(T)$ as indicated by the result and try again until a fit to the experimental curve is found. If, as usual, the range straggling is not great, an approximate but straightforward procedure is the following: let the connection between T and the expectation value, x_0, of x be $T = \omega(x_0)$ (the range energy relation). Then $f(T)dT = H(x_0)dx_0$.

Let $x_0 = x - \epsilon$ and $\partial g/\partial x = \lambda(\epsilon, x)$. Then

$$n(x) = \int_{-\infty}^{\infty} H(x - \epsilon)\, \lambda(\epsilon, x)\, d\epsilon \qquad (10.11.2)$$

We symbolize d^2H/dx^2 by H''. Then for small ϵ

$$n(x) = H(x) \int_{-\infty}^{\infty} \lambda(\epsilon, x)\, d\epsilon + \frac{H''(x)}{2} \int_{-\infty}^{\infty} \epsilon^2 \lambda(\epsilon, x)\, d\epsilon$$

plus terms in higher powers of ϵ.

Since λ is normalized, $n(x) \approx H(x) + [H''(x)/2]\sigma^2(x)$, where σ^2 is the range straggling for range $x \approx x_0$. Therefore, to the same order of approximation:

$$f(T) \approx \left(\frac{dT}{dx_0}\right)^{-1} \left[n(x) - \frac{1}{2} n''(x)\, \sigma^2(x)\right]_{T=\omega(x)} \qquad (10.11.3)$$

This is a good approximation if $n(x)$ is slowly varying and σ small.

10.11.2 Wedge Absorbers

Figure 10.11.1 is the diagram of a simple device designed to measure an energy spectrum of protons. The emulsion is on a 1×3 inch glass

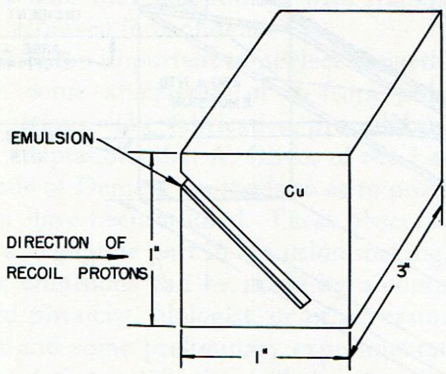

FIG. 10.11.1. A wedge absorber (IDLRL).

plate that is slipped into the slot, its outer 3-inch edge flush with the edge of the copper. The plate is held tightly by tape, so that the emulsion face is against the copper. The plate is scanned after exposure and the y coordinate (the distance from the outer edge of the plate to the point of stopping) is recorded. Then for a thin layer of emulsion $x = y \sin \alpha$, where α is the angle between the normal to the entrance face and the normal to the emulsion plane. If the emulsion is thick, obviously a more exact expression can be used. If the thickness of the emulsion is a, its thickness in the direction of particle motion is $a \sec \alpha$. This is the range in emulsion of a particle with a particular energy T_1. Let the range of a particle of this energy in the absorber (here copper) be b. Then in the emulsion layer all the particles stop that would have stopped in the layer of absorber of thickness $b \cos \alpha$, which it replaces. The number of endings in unit area of the plate at coordinate y is the same as in a volume $b \cos \alpha$ at a depth of penetration $y \sin \alpha$. On substituting $x = y \sin \alpha$ and correcting n, Eq. (10.11.3) can be used for the wedge absorber.

Of course dT/dx_0 is calculated for the particles as they enter the wedge absorber. To avoid secondary effects of scattering, a material such as copper, which somewhat approximates emulsion in scattering behavior is preferred as the absorber.

Figure 10.11.2 is a drawing of a wedge absorber used by Heckman and Bailey (HB 53) in an early meson scattering experiment.

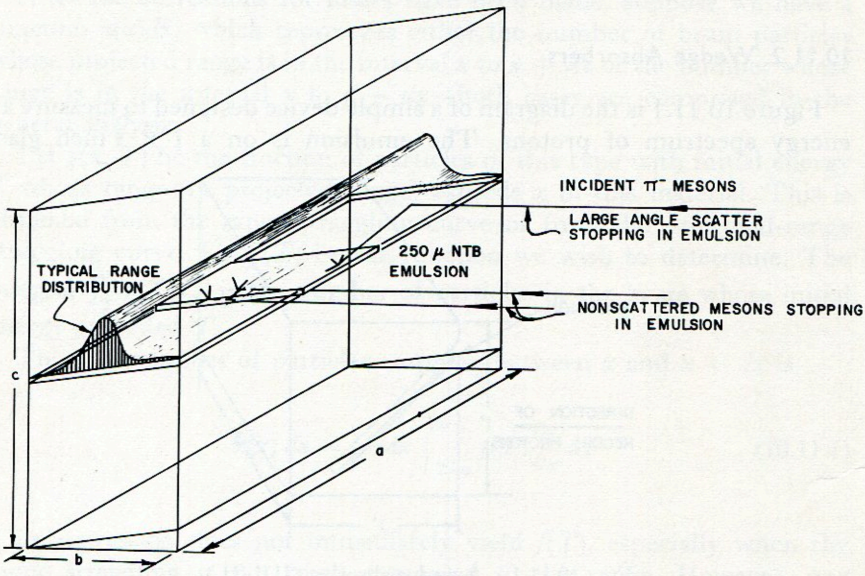

FIG. 10.11.2. A combined scattering target and emulsion detector made in the form of a wedge absorber. This arrangement was used in an early experiment in which the large-angle scattering of pions was measured in aluminium, copper, and lead (IDLRL).

Note on Emulsion Making

The preparation of emulsions suitable for photography or for recording nuclear-particle tracks is often thought to be an obscure art. Because there are many variable factors, and the basic theory is not fully established, some details of production must be developed empirically. Information gained in this way may thereafter remain a closely guarded secret of the manufacturer. Since the writer is not connected with the photographic industry, he obviously cannot discuss this subject with the authority of one in the business. On the other hand, as C. E. K. Mees has stated in the preface to his treatise on "The Theory of the Photographic Process," a person in the industry may not publish with frankness knowledge of the subject that he acquired in confidence.

Because the topic is too important to neglect altogether, the writer has attempted to gain some knowledge of it from published work and his personal observations. The fabrication procedures of P. Demers in Montreal, and the adaptations that A. Oliver of the Lawrence Radiation Laboratory has made of Demers' methods so as to provide better control of the precipitation have been studied. These observations suggest that black magic plays a negligible part in emulsion making, and that rather good nuclear-track emulsions can be made by a competent chemist or chemically inclined physicist, biologist, or other trained scientist with modest equipment and some preliminary experimentation.

Except for the gelatin constitution, all aspects of emulsion making such as temperatures, times, stirrings, precipitation, purity of chemicals, proportions of constituents, etc., appear to be subject to absolute control. Sufficiently close tolerances can be set on each to insure reproducible results. Special quality control is therefore demanded only for the gelatin.

The first stage of the manufacture of silver halide-gelatin emulsions is carried out with three solutions: (A) a solution containing a soluble silver salt, usually silver nitrate; (B) a solution normally containing halide salts, perhaps chiefly KBr; (C) a warm solution of a photographic gelatin. In the procedure used by Demers (D 54), solution A contains 600 gm of $AgNO_3$ in a liter of solution weighing 1482 gm, and solution B contains 420 gm of KBr per liter of solution weighing 1288 gm.

Equal volumes of these solutions contain silver and bromine in approximately the stoichiometric ratio, the silver excess being 5 parts in 7000. Demers prepares solution C using 225 gm of gelatin (number 2191, American Agricultural Chemical Company, Keystone brand) dissolved in 1500 gm of cold water in a stainless-steel vessel 20 cm in diameter and 27 cm high. The gelatin is swelled for 1 hr and is then melted in a hot water bath at 50°-55°C. Demers then adds 900 ml of alcohol to help remove bubbles, and keeps the mixture covered at 48°C.

Solutions A and B are connected to stainless-steel metering pumps which can deliver fluid quite accurately in a ratio of 1911 ml of solution A to 1950 ml of solution B. A stirrer is started in solution C and 1 ml of solution B is added to it so as to start precipitation with a bromide excess. Then solutions A and B are pumped into the gelatin solution through separate glass tubes drawn out to tips which may be inserted into the gelatin solution. This is done to prevent splashing and possible reaction of the solutions in the absence of gelatin, causing coarse fog. Stirring is carried out with a fiber paddle on the end of a stainless-steel shaft. The rotation is as vigorous as possible without spilling or creating bubbles. Only a red light is permitted. The heat of reaction is sufficient to keep the temperature at 48°C, but a water-jacketed precipitation vessel can be used to keep the solution temperature at any desired value. Temperatures anywhere in the interval of 35° to 48°C appear to be satisfactory. (A variation of the procedure uses three jets, and the three solutions are introduced in constant ratios throughout the precipitation period.)

The emulsion is cooled to 12°-15°C with hand stirring. It is kept overnight at 0°-5°C and is then shredded by being placed in a fiber tube fitted with a piston, and in the bottom of which is a stainless-steel mesh with 1- or 2-mm apertures through which the emulsion is pressed. The shredded emulsion is washed in water at a temperature between 5° and 10°C for at least 2 hr until it is thoroughly washed. The washing may conveniently be carried out in a percolator with a stainless-steel mesh bottom. The water passes up through the mass of shredded emulsion which is stirred occasionally to separate the "noodles" of shredded emulsion. The drained shreds, which are now ready for sensitization, may be kept for a few days at 0°-5°C.

To one-third of the shreds, melted at 50°C, 13.5 gm of triethanolamine, 0.5 gm of thymol, and 100 ml of alcohol in one solution are added. To prepare pellicles 300 $\pm$ 30 μ in thickness, Demers proceeds as follows: The emulsion is poured at 35°-40°C from the bottom tip of a medical "irrigator" through a rubber tube. To avoid air bubbles the liquid is taken from the bottom. The emulsion is poured on to a piece of glass 24 by 36 inches leveled very carefully. The emulsion is prevented from flowing off the edges by lucite bars cemented down with 8% gelatin or cellulose acetate cement. The tray measurement is 78 cm by 53 cm. The emulsion sets in 1/2 hr or so. Initially it is about 3-mm thick. It is dried with a slow flow of air at 25°C and at 67 ± 3% R. H. for at least 2 days. More rapid drying is inadvisable. The resulting sheet of emulsion can be cut into 75 2 by 4 inch pellicles. When the two remaining thirds of the emulsion are also sensitized and poured, a total of 225 pellicles are obtained from the original solutions.

Perfilov, Novikova, and Prokofyeva (PNP 57) reported that, if a small excess of silver nitrate over the equivalent amount of potassium bromide is maintained during the entire process of emulsification until the emulsion is chilled, then emulsion with grains that are very small and uniform is obtained. They have been able to exercise good control by means of potentiometer monitoring of the silver ion concentration.

Oliver has constructed apparatus by which control is carried out automatically at a slow and controlled precipitation rate. The rate of pumping is 1.7 ml of solution A per minute.

A recording and controlling potentiometer is connected to a silver electrode and a calomel electrode. The silver electrode is placed in the precipitation vessel for which Oliver uses a glass beaker. A U-tube filled with silver nitrate-saturated agar acts as a bridge to link the emulsion to potassium nitrate solution in a second beaker, and another U-tube filled with KCl-saturated agar provides a second electrical link to a beaker containing a KCl solution. In this solution a calomel electrode is placed. The potential differential difference observed with the potentiometer measures the relative concentration of silver ions in the precipitation vessel. An end point of the precipitation is determined by a preliminary titration. The standard ratio of solutions B and C are mixed together. While stirring, this is titrated with solution A to the KBr end point. The end point is determined with the potentiometer. When it is approached each successive drop of silver nitrate solution has a larger and larger effect on the potentiometer reading. As the end point is passed, the effect becomes smaller again. The potentiometer reading at which the effect of a single drop causes the maximum change in the potentiometer deflection is recorded, and is taken as the end point. The potentiometer is normally connected so that increasing silver ion content corresponds to higher potentiometer readings. A silver excess exists when the potentiometer reads less than the end point.

Now, using the potentiometer in a servo-mechanism linkage by which the output of the potentiometer controls the ratio of solutions A and B admitted to the precipitation vessel, exceedingly good control of the precipitation can be obtained. The crystals can be caused to form in any desired excess of silver or bromide, thus varying the ripening and crystal size.

The actual mechanism operates as follows. Metering pump A pumps solution A through jet A at a constant rate. Metering pump B pumps solution B out of jet B also at a constant rate somewhat below the equivalent rate of A. A third small pump, the speed of which is controlled by the potentiometer, also pumps solution B through jet B. The amount of silver or bromine excess is set in the potentiometer, and the system varies the speed of the vernier pump to maintain the desired silver-calomel electrode potential difference. Because of the danger of corrosion, the pumps actually pump mineral oil which displaces the reacting solutions.

If someone were to set out to produce an emulsion with particular properties it would appear that a logical and scientific, if empirical, approach to the problem would be first to reproduce Demers' results. This Oliver has shown can be done, so that one may start with confidence and produce from the beginning a useful product.

Next it seems that the Perfilov-Oliver refined potentiometer control of the precipitation might well be adopted. It would be obvious to proceed thence with *small* variations of *one* parameter at a time while optimizing each of the others to the altered conditions. For example, if the gelatin is changed, the optimum $AgNO_3$: KBr ratio among other things probably will shift slightly. Professional emulsion makers have a very broad base of experience with the components of emulsion manufacture, but for an amateur the possible avenues of research to obtain desired properties in a nuclear-track emulsion must be investigated as if for the first time. Some of the variations that can be explored are introduction of iodide into the crystals, introduction of sulfur compounds and glycerin into the precipitation and emulsification. One can also study maturation and grain growth produced by variation of temperature, time, hydrogen, and silver ion concentration in the post precipitation period, introduction of various other organic sensitizers as well as gold, rhodium, and sulfur compounds. A drastic change is to try other gelatins. These are not small changes and it may be wise to start by blending in another product, watching the transition in gradual stages. Of course, many of these variations have been investigated by Demers, but the possible useful combinations of chemicals and ripening treatments are nearly infinite.

This fact is illustrated by the work of Jenny (J 51), who has made electron-sensitive emulsions under quite different conditions. His solution A is 20 gm of silver bromide in 30 ml of distilled water; his solution B is 14.8 gm of potassium bromide, 0.6 gm of potassium iodide, 7 ml of a 10% solution of hydrated cadmium bromide, and 23 ml of distilled water; while his solution C is 3.6 gm of gelatin (No. 3202 Winterthur), 1 ml of 6-nitrobenzimidazole 1 : 500, and 60 ml of distilled water. Precipitation was at 37°C, carried out using burettes for solutions A and B and maintaining a small bromide excess. This took 30 min. After 32 min, exactly 6 ml of concentrated ammonia was added and stirred. Then after 5 min, 4.5 gm of citric acid neutralized the ammonia. The grain size and sensitivity were stated to be increased by this treatment. After shredding and washing, the emulsion is remelted and chromalum, glycerin, and an alcohol solution of organic sensitizer are added before pouring.

There are complicating aspects even to Demers' process. The gelatin he employs has a considerable chloride content, so that his precipitate is a mixture of bromide and chloride, and perhaps Demers' emulsions depend to some extent on the presence of the chlorine for sensitization of the crystals.

The control of grain size and uniformity is not a simple question either. The growth of grains is slowed by the adsorption to the grain surface of organic substances from the gelatin or by synthetic materials added to the emulsion to inhibit grain growth. For example, this function has been attributed to a silver compound of thiolactic acid. Many interesting experiments on the control of grain size by such methods doubtless remain to be carried out.

Note on Mounting and Processing for Kodak Nuclear-Track Pellicles, Type NTB 4, 600 Micron

With a communication dated March 15, 1962, the writer received from the Eastman Kodak Company a technical data sheet in which detailed processing procedures were recommended for their type NTB 4 emulsions. These are similar in the main to the procedures discussed in Chapters 4 and 5, but enough differences exist to justify an extensive section from their instructions to be included here.

Safelights

The light sensitivity of these emulsions is four or five times greater than that of emulsions normally used in this work. Hence, care must be taken in the choice of safelights and of grid exposures. The performance of the safelight depends on the wattage of the lamp and the distance between the safelight and emulsion. The use of a Wratten No. 2 Safelight with a 15-watt bulb is recommended for trial.

Mounting Gel Solution

Distilled water at 20°C	1000 ml
Kodak mounting gelatin	15 gm
Glycerol	5 ml
Kodak Photo-Flo	2.5 ml

Soak the mounting gel overnight in the distilled water at room temperature. Heat the container in a water bath at a temperature not to exceed 50°C. The heating should be maintained until the gel is in solution. Without the use of agitation, about 2 hr is required. If the solution is agitated, care must be exercised to prevent the inclusion of air in the solution. Filter the solution to remove any dirt or undissolved gel particles. Add the glycerol and Photo-Flo and cool the solution to

27°C. A temperature of 27°C should be maintained during the subsequent pellicle mounting operation.

Pellicle Mounting Procedure

One of the Kodak gel-coated plates (furnished with the pellicles) and the pellicle to be mounted should be immersed in the gel mounting solution at the same time. The pellicle should be allowed to slide into position on the plate with care being used to prevent trapping air between the two surfaces. Care must also be taken to prevent the gel coating of the plate from becoming too soft. Total immersion times of the order of 5 to 10 sec have been used. The plate and pellicle should then be passed, under moderate pressure, between the rollers of a hand-operated clothes wringer. The pellicle surface should then be blotted with filter paper to remove excess solution. The mounted pellicle is then ready for processing. It should be placed in a rack constructed in a manner to maintain the plane of the plate in a horizontal position throughout the forthcoming process. Processing is begun approximately 15 min after the last pellicle is mounted. This time is not critical.

Processing Solutions

(A) *Cold soak solution**

Distilled water at 20°C	1000 ml
Sodium sulfite (Na_2SO_3), desiccated	18.0 gm
Boric acid	37.0 gm
Potassium bromide	0.8 gm

Supplied with the above, but not added until just prior to use of the solution, 4.5 gm of amidol (2,4-diaminophenol dihydrochloride).

(B) *Developing solution**

Distilled water at 20°C	1000 ml
Sodium sulfite (Na_2SO_3), desiccated	9.0 gm
Boric acid	18.5 gm
Potassium bromide	0.4 gm

Supplied with the above, but not added until just prior to use of the solution, 2.25 gm of amidol (2,4-diaminophenol dihydrochloride).

* Solutions A and B should be made on the day preceding the start of the process, and the amidol added as above just before use.

(C) *Stop bath solution*

Distilled water	970 ml
Glacial acetic acid	30 ml

(D) *Fixing bath solution*

Distilled water	1000 ml
Sodium thiosulfite (hypo)	400 gm
Sodium bisulfite	30 gm

(E) *Glycerol bath*

Distilled water	950 ml
Glycerol	50 ml

Processing Times and Temperatures

Cold soak at 5°C	2 hr
Developer at 23°C*	30 min
Stop bath at 5°C	1.5 hr
Fixing bath at 5°C	72 hr
Wash at 5°C	72 hr
Glycerol bath at 10°C	30 min
Drying in air at 20°C, 50% RH.	24-36 hr

Processing Procedures

(A) *Cold soak*

Cool the cold-soak solution to 5°C in the airtight container(s) in which it has been kept. Pour the solution into the processing tank and maintain the temperature at 5°C. Just prior to placing the mounted pellicles in the solution, add the amidol and stir the solution gently. Leave the pellicles in the solution for 2 hr at 5°C with no agitation.

(B) *Developer*

Heat the developer solution to 23°C in the airtight container(s) in which it has been kept. Pour the solution into a processing tank and maintain the temperature at 23°C. Just prior to the removal of the pellicles from the cold solution and their insertion in the developer, add the amidol and stir the solution gently. Remove the pellicles from the

* This time may be varied according to requirements.

cold soak solution, drain briefly, and insert in the developer. The developing time will depend on the particular experiment being run and upon any grid exposures placed on the pellicle by the experimenter. Times of the order of 1/2 hr have been used.* No agitation should be used during the development.

(C) *Stop bath*

Cool the stop bath solution to 5°C, pour into a processing tank, and maintain at 5°C. At the conclusion of the developing period, remove the pellicles from the developer, drain briefly, and insert in the stop bath. The pellicles should be left in the stop bath without agitation for $1\frac{1}{2}$ hr.

(D) *Fixing bath*

Cool the fixing bath solution to 5°C. This may be done in the fixing bath tank during the preceding process steps. At the conclusion of the stop bath period, remove the pellicles, drain briefly, and insert in the fixing bath solution. The entire fixing operation is done at 5°C and is the first step of the process which requires solution agitation. A recirculation system which assures a laminar flow across the surface of the horizontal pellicles at the rate of 1 cm per second has been used. The fixing time employed is approximately one and one-half the time required for clearing. This requires a total fixing time of approximately 72 hr.

The fixing bath should be replenished in two stages with a volume of solution equal to the original volume. The replenishing solution is identical in composition to the fixing bath solution and should be cooled to 5°C before being added. The first half of the replenishing solution should be added after about 16 hr of fixing and the second half about 20 hr after fixing commences. The solution should be added in such a manner that thorough mixing of the fixing bath and the fresh solution is assured. Solution equal in quantity to that being added should be removed from the processing tank while the replenishing operation is taking place. The removed solution is then a mixture of the used and fresh solution. The same procedure is used for both stages of replenishment, and is designed to minimize the shock to the pellicles inherent in the addition of fresh solution.

(E) *Washing*

A continuous supply of fresh water at 5°C is required for washing. At the conclusion of the fixing operation the washing operation is begun

* This time may be varied according to requirements.

in the same processing tank without removing the fixing solution. This assures a dilution procedure, but one which occurs rather rapidly. The washing rate is identical to the circulation rate used in the fixing operation. The total duration of the wash is identical to that of the fixing period.

(F) *Glycerol bath*

At the conclusion of the wash the racks should be removed, drained briefly, and inserted in the glycerol bath which has been cooled to 10°C. The duration of this bath should be 1/2 hr with the temperature maintained at 10°C.

(G) *Drying*

At the conclusion of the glycerol bath the pellicles should be removed, blotted with filter paper, and placed on a drying rack in a horizontal position. Drying is accomplished at room temperature (20°C) in a 50% R. H. atmosphere. Total drying time is on the order of 24 to 36 hr.

Mathematical and Physical Data*

Atomic Constants

$N = 6.025 \times 10^{23}$ molecules/mole (Avogadro's number)
$c = 2.99793 \times 10^{10}$ cm/sec (velocity of light)
$e = 4.80286 \times 10^{-10}$ esu $= 1.6021 \times 10^{-19}$ coul (quantum of charge)
$e^2 = 1.44 \times 10^{-13}$ Mev cm
1 Mev $= 1.602 \times 10^{-6}$ erg
$\hbar = 6.5817 \times 10^{-22}$ Mev sec $= 1.054 \times 10^{-27}$ erg sec
$\hbar c = 1.9732 \times 10^{-11}$ Mev/cm
$k = 8.6167 \times 10^{-11}$ Mev/°C (Boltzman constant)
$\alpha = e^2/(\hbar c) = 1/137.037$ (fine-structure constant)
$M_1 = (1/16)O^{16} = 931.141$ Mev (atomic mass unit)
$M_2 = (1/12)C^{12} = 931.441$ Mev (new atomic mass unit)
$m = 0.510976$ Mev $= 9.1085 \times 10^{-28}$ gm (electron mass)
$M = 938.213$ Mev $= 1.6724 \times 10^{-24}$ gm (proton mass)
$m_\pi = 139.59$ Mev $= 2.488 \times 10^{-25}$ gm (pion mass)
$r_\pi = \hbar/(m_\pi c) = 1.4136 \times 10^{-13}$ cm (pion Compton wavelength)
$\gamma_0 = e^2/(mc^2) = 2.81785 \times 10^{-13}$ cm (electron radius)
$\lambda\!\!\!^{-}_c = \hbar/(mc) = r_e/\alpha = 3.8612 \times 10^{-11}$ cm (electron Compton wavelength)
$a_0 = \hbar/(me^2) = r_e/\alpha^2 = 0.52917 \approx \times 10^{-8}$ cm (Bohr radius)
$R_\infty = me^4/(2\hbar^2) = mc^2(\alpha^2/2) = 13.605$ ev (Rydberg)
$(8/3)\pi r_c^2 = 0.6652 \times 10^{-24}$ cm^2 (Thompson cross section)
$e\hbar/(2mc) = 0.57883 \times 10^{-14}$ Mev/gauss (Bohr magneton)
$\hbar/(m_\pi c^2) = 4.715 \times 10^{-24}$ sec (nuclear time)
$\pi r_\pi^2 = 6.278 \times 10^{-26}$ cm^2 (geometrical cross section of nucleon)
($\pi r_\pi^2 A^{2/3}$ is often taken as the geometrical cross section for nucleus of mass number A)

General Physical Constants and Definitions

Gravitational constant $= 6.670 \times 10^{-8}$ dynes cm^2/gm^2
Faraday (1960) $= 96{,}516$ coul (physical scale—based on O^{16})
$= 96{,}489$ coul (chemical scale—based on O_2)

* Largely from W. H. Barkas and A. H. Rosenfeld, University of California, Lawrence Radiation Laboratory report, UCRL-8030 Rev.

Year (365 days) = 3.1536×10^7 sec
Density of air = 1.205 gm/l at 20°C and 1 atmosphere
1 atmosphere = 1033.2 gm/cm^2
1 calorie = 4.184 joules
absolute zero = −273.16°C
1 micron (μ) = 10^{-6} meters = 10^{-4} cm
1 barn = 10^{-24} cm^2
1 Å = 10^{-8} cm
1 fermi = 10^{-13} cm
1 curie = 3.7×10^{10} disintegrations per sec
1 roentgen = 87.8 ergs/gm of air = 5.49×10^7 Mev/gm of air (about 3×10^7 minimum ionizing particles per square centimeter in carbon)

Numerical Constants

$\pi = 3.14159$
1 degree = 17.4533 milliradians
1 radian = 57.29578 degrees
$\epsilon = 2.71828$ (base of natural logarithms)
$\ln 2 = 0.69315$
$\ln 3 = 1.09861$
$\ln 10 = 2.30259$
$\ln \pi = 1.14473$
$\log_{10} e = 0.43429$
$\log_{10} 2 = 0.30103$
$\log_{10} 3 = 0.47712$
$\log_{10} \pi = 0.49715$
$\gamma = -\Gamma'(1)/\Gamma(1) = 0.577216$ (Euler's constant)

Useful Formulas

Stirling's approximation:

$$(2\pi n)^{1/2}\,(n/\epsilon)^n < n! < (2\pi n)^{1/2}\,(n/\epsilon)^n\left(1 + \frac{1}{12n - 1}\right)$$

Gaussian distributions and gamma functions:

$$\int_0^\infty x^{2n+1} \exp\left(\frac{-x^2}{2\sigma^2}\right) dx = 2^n \sigma^{2n+2}\, n! \quad \text{for } n > -1$$

Note that: $n! = \Gamma(n + 1) = n\Gamma(n)$, and in particular $(1/2)! = \Gamma(3/2) = (1/2)\Gamma(1/2) = (1/2)\pi^{1/2}$

Generalization of volume of a sphere to n dimensions:

$$V_n = \frac{\pi^{n/2}}{(n/2)!} R^n$$

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