TABLE III. Total cross section.

k	3	4	6	10	20
Eq. (4)	0.0876(0)	0.3265($\pm$1)	0.9096($\pm$8)	1.950($\pm$2)	3.69($-$2)
Heitler	0.085	0.32	0.89	1.94	3.75
Eq. (1)				1.89	3.73($+$2)

where we have also reproduced results given by Heitler,[4] and at $k=10, 20$ numbers from the high energy formula (1). The figures in parentheses are expected errors in the last digit shown. One should note the considerable improvement in accuracy over Heitler's results, and the overlap of (4) and (1) at $k=20$. At $k=15$, the two are still closer.

The low energy form of (2), $\phi_z = \phi_0 z$, was found by expanding the exact formula in powers of the excess energy, $k-2$; the limiting k-dependence found for ϕ_0 is

$$\phi_0 = (\tfrac{1}{3})(k-2)^3 \quad (k-2)\ll 1. \tag{5}$$

(5) is interesting in that the coefficients of three lower powers of $(k-2)$ vanish, so there results a higher order of contact of the total cross section curve at $k=2$ than might have been expected. The range of validity shown in (5) must be taken seriously: at $k=2.5$ (5) is already almost double the true value. As pointed out to me by Professor H. A. Bethe, multiplying (5) by $(2/k)^3$ gives the best possible power law approximation for large k; the improved formula is 12 percent low at $k=3$, 50 percent low at $k=6$, and gives a total cross section at high energies $\sim$2 instead of actual limits (if screening is included) of $\sim$12.

I wish to thank Professor Bethe for suggesting these calculations and for helpful discussions of many points while carrying them out.

[1] H. Bethe and W. Heitler, Proc. Roy. Soc. 146, 90 (1934), Eq. (21); or W. Heitler, Quantum Theory of Radiation (Oxford University Press, 1936), p. 196, Eq. (8).
[2] W. Heitler, Quantum Theory of Radiation (Oxford University Press, 1936), p. 197, Eq. (9).
[3] See reference 2, p. 200, Eq. (15).
[4] See reference 2, p. 200, Table V.

On the Structure of Grain Boundaries in Metals

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THERE is no method known at present of determining the structure of grain boundaries in metals. Considerations based on the atomistic viewpoint suggest that the grain boundary is a transition region, where the atom positions represent a compromise between the crystalline arrangements in the two adjoining grains. Extensive experiments on internal friction and related effects have demonstrated that this transition region behaves in a viscous manner in the sense that it cannot sustain permanently a shear stress and it has a coefficient of viscosity decreasing with an increase of temperature.[1,2] This does not, however, tell us about the structure of this transition region, since any layer of disturbed crystallinity when considered as an entity may manifest a viscous behavior.

A study of the activation energy associated with the viscous slip along grain boundaries seems to contribute to our understanding of the structure of the grain boundary. It has been found that the activation energy associated with the grain boundary slip in alpha-brass is close to the value for the diffusion of zinc in alpha-brass of the same composition.[3] Recently, in the study of the anelastic effects in alpha-iron,[4] the value obtained for the activation energy of grain boundary slip agrees, within experimental error, with the value for the self-diffusion in alpha-iron reported by Birchenall and Mehl.[5] Such an agreement has also been found in the case of aluminum. The activation energies for volume diffusion and grain boundary slip of these metals are summarized in the second and third columns of Table I.

If such an agreement in activation energies were found to be a general phenomenon in all metals, this would indicate that the grain boundary slip involves the same mechanism as does volume diffusion. This would also indicate that, at least as far as the local order is concerned, the structure of the transition region at the grain boundary cannot be markedly different from that of the interior of the grains. The grain boundary slip can thus be considered as creep on a microscopic scale, and this creep occurs at a lower temperature than creep in single crystals because of the disturbed crystallinity at the grain boundary. This viewpoint is strengthened by the findings that the activation energies for the creep in these metals (shown in the fourth column of Table I) are comparable with that of grain boundary slip.

The upper limit of the width of grain boundary has been suggested to be five atomic diameters on the basis that the forces between atoms in solids are of short-range type extending with appreciable intensity only over a few atomic distances.[6] It seems that the boundary region within which creep may take place must have a width of at least a few atomic diameters. Actually the mere fact of short-ranged forces in solids does not necessarily imply that the transitional region can only be very thin. Reference can be made

TABLE I. Different types of activation energy of a few metals (in calories per mole).

Type of metal	Volume diffusion	Grain boundary slip	Creep
Alpha-brass	41,700[a],*	41,000[b],*	42,000[a],**
Alpha-iron	78,000[d],***	85,000[a],***	90,000[f]
Aluminum	37,500[e]	34,500[b],†	37,000[i],†

* 29 percent Zn.
** 40 percent Zn.
*** Westinghouse Puron.
† 99.99 percent aluminum.
[a] A. E. Van Arkel, Metallwirtschaft 7, 656 (1928); see also R. F. Mehl, Trans. A.I.M.E. 122, 11 (1936).
[b] See reference 3.
[c] H. Tapsell, A. Johnson, and W. Clenshaw, Eng. Research Report No. 18, Dept. Sci. and Ind. Research, London (1932).
[d] See reference 5.
[e] See reference 4.
[f] J. J. Kanter, Trans. A.I.M.E. 131, 385 (1938).
[g] Estimated on the basis of binding energy and of melting temperature according to an empirical rule for face-centered cubic metals observed by W. A. Johnson, Trans. A.I.M.E. 143, 107 (1941); also private communication to the writer.
[h] See reference 1.
[i] S. Dushman, L. W. Dunbar, and H. Huthsteiner, J. App. Phys. 15, 108 (1944); extrapolated to zero stress by C. Zener and J. H. Hollomon, J. App. Phys. 17, 69 (1946).

to magnetic domain boundaries the width of which has been computed to have a value of between 30 to 100 atomic diameters.[7]

[1] T. S. Kê, Phys. Rev. **71**, 533 (1947).
[2] T. S. Kê, Phys. Rev. **72**, 41 (1947).
[3] T. S. Kê, J. App. Phys. (in the press).
[4] T. S. Kê, communicated to Trans. A.I.M.E.
[5] C. E. Birchenall and R. F. Mehl, Mining and Metallurgy (November 1947).
[6] F. Seitz and T. A. Read, J. App. Phys. **12**, 538 (1941).
[7] F. Bloch, Zeits. f. Physik **74**, 293 (1932); also R. Becker and W. Dorng, *Ferromagnetismus* (Verlag Julius Springer, Berlin, 1939), p. 189.

Erratum: Interaction of Neutrons with Electrons

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IN a recent letter to the editor[1] we erroneously estimated the expected scattering cross section of neutrons on electrons due to the polarization of the meson cloud in the field of an electron. While this effect no doubt exists theoretically it is much less important than the effect due to the spreading of the meson charge over a finite region in the nucleus as shown in the recent paper by Fermi and Marshall.[2] The conclusion at the end of the letter must therefore be withdrawn.

[1] J. M. Jauch and K. Watson, Phys. Rev. **72**, 1254 (1947).
[2] E. Fermi and L. Marshall, Phys. Rev. **72**, 1139 (1947).

Structure, Electrical, and Optical Properties of Barium Titanate*

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SEVERAL letters to the editor have appeared recently in this journal[1,2] and in Nature[3,4] dealing with observations on $BaTiO_3$. Since some of the statements made are somewhat misleading, and others present results anticipated by publications from this Laboratory,[5] a short account concerning the properties of barium titanate as they appear today on the basis of our recent investigations may be in order.

N. J. Field, A. P. DeBretteville, and H. D. Williams reported[1] two kinds of barium titanate crystals with different infra-red absorption, distinguishable by their bluish and yellowish colors. This coloration is due to dissolved platinum, and we can add to the color scale crystals from light green to deep red by varying the method of growing the material in Pt crucibles. The pure crystals without oxygen defect are colorless and may, for instance, be grown with the proper precautions in carbon crucibles.

A microscopic investigation reveals that, regardless of color, the crystals are subdivided into ferroelectric domains. The faces of these domains parallel to the polar axis are, in general, covered with a system of stripes oriented at 45° to the cube edges and apparently represent slip bands. In the direction of the polar axis the crystals appear clear and sometimes intersected by stripes parallel to the cube edges. In polarized light the structure of the domains is enhanced by various stress colors, and black boundary lines mark the regions in which the opposing stresses of several domains balance.

By the application of an electric field, the domain boundaries may be seen to shift some domains growing at the expense of others, and, finally, the polar axes change orientation in sudden jumps by 90° or 180°. Increase of the temperature to the Curie point makes first the 45° stripes and then the domains themselves disappear; they reappear on cooling in various arrangements, depending on the thermal history. By cooling in an electric field from above the Curie point, the whole crystal may be forced more or less into a single domain, but such a state breaks down later into several domains forming arrangements of lower energy. The domain structure can also be influenced by pressure; in short, all the domain phenomena derived by indirect evidence in the case of ferromagnetics can be made visible in these ferroelectric crystals.

$BaTiO_3$ crystals are generally biaxial because of the stresses set up by their domains, but we have succeeded in producing single crystals of such large domain areas that they appear nearly tetragonal in polarized light. According to our present evidence, the c axis represents the polar axis, and can be turned in electric fields; x-ray backreflection photographs of these large domains are being made to decide the question.

At low field strength, the dielectric constant parallel to the polar axis is relatively small ($\cong 600$ at 25°C) and, perpendicular to it, is high ($\cong 2000$ at 25°C); they are nearly alike in the two latter directions. The crystals are piezoelectric, and their resonance vibrations disappear as the dielectric constant begins to increase towards its maximum. The vibrations of titania ceramics, discovered by Roberts in this Laboratory, should, therefore, not be treated as an electrostrictive phenomenon as done by Mason,[2] because a normal electrostrictive effect increases with dielectric constant.[6] The mechanical deformation of $BaTiO_3$ single crystals appears as the superposition of a linear and a quadratic piezo effect.

In addition to the cubic modification of $BaTiO_3$, there exists, among others, an hexagonal form[7] which is not ferroelectric.

A more extensive paper on titania single crystals and their interaction in ceramics is in preparation. Photographs of the domain effects will be shown at the annual meeting of the American Physical Society in New York.

[1] N. J. Field, A. P. DeBretteville, Jr., and H. D. Williams, Phys. Rev. **72**, 1119 (1947).
[2] W. P. Mason, Phys. Rev. **72**, 869 (1947).
[3] H. F. Kay and R. G. Rhodes, Nature **160**, 126 (1947).
[4] J. K. Hulm, Nature **160**, 127 (1947).
[5] A. von Hippel, R. G. Breckenridge, F. G. Chesley, and L. Tisza, J. Ind. Eng. Chem. **38**, 1097 (1946); S. Roberts, Phys. Rev. **71**, 890 (1947); B. T. Matthias, R. G. Breckenridge, and D. W. Beaumont, Phys. Rev. **72**, 532 (1947).
[6] *Handbuch der Physik* XII, 493, 556.
[7] H. Blattner, B. Matthias, and W. Merz, Helv. Phys. Acta **20**, 225 (1947).