conductivity observed in alkali halides subsequent to plastic deformation may be partially electronic in origin. Gyulai and Boros studied single crystals of KCl and KBr. The technique was the same as that of Gyulai and Hartley except that use of a vacuum tube electrometer and recording oscillograph in place of a string galvanometer permitted closer observation of times involved in current changes and greater current sensitivity. Stresses of only about 10^7 dynes/cm^2 produced detectable current changes. Half-times for decay of the enhanced conductivity were now observed to be about 0.2 second with no appreciable fraction of the induced current changes persisting for greater than several seconds. The rise time of the current change was observed to be 0.1 second, but it is not clear whether this time is characteristic of the deformation process or represents a limitation of the detection system.

Gyulai and Boros also found that current changes induced by deformation in KCl and KBr crystals colored additively, or by x-rays to about 10^{17} F-centers per cm^3, were approximately twice the magnitude of current changes induced in uncolored crystals under similar conditions of stresses and field strength. However, the times involved in decay of the current changes were the same for colored and uncolored crystals.

Both the short duration of current changes and the sensitivity to coloration suggest that the increased conductivity observed by Gyulai and Boros may be due to electrons liberated in the vicinity of slip planes during plastic flow. The longer times observed by Gyulai and Hartly may be associated with continued plastic flow due to higher stresses rather than the mechanism of conduction. They show evidence (Fig. 4 and Fig. 5, reference 1) that both the work hardening and the dimensional change induced in a specimen subsequent to a suitable increase in stress, continue for a time comparable to the decay time of the current change produced. The authors point out that as plastic flow continues for some time after loading it is not valid to assume that the charge is all liberated at the initial moment of the flow process. Thus the times involved in current decay may represent continued liberation of electrons during a flow process rather than the diffusion of vacancies to clusters or boundaries.

It is reasonable to expect the duration of flow to be much shorter with the considerably lower stresses used by Gyulai and Boros. Independent evidence that stresses of 10^7 dynes/cm^2 are sufficient to produce well-defined slip in alkali halides and in particular in KCl is cited by Schmid and Boas.[4]

Although the work of Gyulai and Boros does not provide evidence that vacancies are not generated during plastic flow, it does suggest that the current changes observed by Gyulai and Hartly do not provide unambiguous evidence for the vacancy generation hypothesis. Experiments at temperatures low enough to completely quench any conductivity due to vacancy diffusion will probably be necessary before current changes observed may be definitely labelled as electronic.

* The Knolls Atomic Power Laboratory is operated by the General Electric Company for the AEC.

[1] Z. Gyulai and D. Hartly, Z. Physik **51**, 378 (1928).
[2] F. Seitz, Phys. Rev. **80**, 239 (1950).
[3] Z. Gyulai and J. Boros, Math. naturw. Anz., ungar Akad. Wiss. **59**, 115 (1940). (Translation from the Hungarian given by the General Electric Company Main Library, Schenectady, New York.)
[4] E. Schmid and W. Boas, *Plasticity of Crystals* (F. H. Hughes Company, London, 1950), p. 234.

Pseudoscalar Coupling in Pseudoscalar Meson Theory

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IT is well known that, in pseudoscalar Yukawa theory, the pseudoscalar and pseudovector coupling types are equivalent within certain limitations.[1] Independent of perturbation expansions, the relationship between the two theories (omitting electromagnetic effects) is most clearly established by Foldy's transformation.[2] Starting out with the Lagrangian of the pseudoscalar coupling, charge-symmetric theory

$$L=L_\varphi-\bar\psi(\gamma_\nu\partial/\partial x_\nu+M)\psi-ifM\bar\psi\gamma_5\tau_\alpha\psi\varphi_\alpha,$$
$$L_\varphi=-\tfrac{1}{2}[(\partial\varphi_\alpha/\partial x_\nu)^2+\mu^2\varphi_\alpha{}^2], \quad (1)$$

and applying the transformation

$$\psi=U\psi', \quad U=\left(\frac{1-if\gamma_5\tau_\alpha\varphi_\alpha}{1+if\gamma_5\tau_\alpha\varphi_\alpha}\right)^{\frac{1}{2}}$$
$$U^{-1}=U^*=\gamma_4U\gamma_4,$$

one finds for L (1) the new form

$$L=L_\varphi-\bar\psi'(\gamma_\nu\partial/\partial x_\nu+M[1+f^2\varphi_\alpha{}^2]^{\frac{1}{2}})\psi'$$
$$-\tfrac{1}{2}fi\bar\psi'(\gamma_5\gamma_\nu\tau_\beta\psi'\partial\varphi_\beta/\partial x_\nu)[1+f^2\varphi_\alpha{}^2]^{-1}, \quad (2)$$

which becomes the pseudovector coupling Lagrangian if the terms $f^2\varphi_\alpha{}^2$ are neglected (in two places). For obtaining approximate equivalence, a first requirement is

$$f^2\varphi_\alpha{}^2\ll1, \quad (3)$$

effectively. This suggests a power expansion whose leading terms, besides the free field Lagrangians, are

$$L'=-\tfrac{1}{2}fi\bar\psi'\gamma_5\gamma_\nu\tau_\beta\psi'\partial\varphi_\beta/\partial x_\nu, \quad (4)$$

$$L''=-\tfrac{1}{2}Mf^2\bar\psi'\psi'\varphi_\alpha{}^2. \quad (5)$$

As to L'', it is true that it contains mostly "mass effects" (Dyson[1]), i.e., terms to be subtracted in any renormalization procedure. Nevertheless, L'', even as a first-order perturbation, gives rise to such processes as the scattering of mesons by nucleons, and meson pair creation by nucleons (in the presence of external nuclear fields). In the second order, L'' also contributes to the nuclear forces.[3] Since L'' carries the large factor M, it is clear that the nth-order effects of L'' will outweight the $(2n)$th-order effects of L' unless mesons with momenta $>M$ play a predominant role.

The condition (3) actually characterizes L' as a weak perturbation; not so L''. It is obviously desirable to treat L'' in a more adequate manner, and this is known to be possible because L'' happens to be the interaction of the scalar pair theory. This theory has been worked out[4] in a static approximation ($\bar\psi'\psi'\rightarrow\Sigma_s\delta(\mathbf{x}-\mathbf{x}_s)$; a charged φ field only was considered, but the inclusion of neutral mesons is trivial). The neglect of nuclear recoils falsifies, of course, the contributions of high energy virtual mesons; but a cutoff, introduced *ad hoc*, eliminates these contributions. In the application to the problem (1) or (2), choosing the cut-off energy in the order of M will ensure qualitatively reliable results.

The rigorous static solutions show, then, that the effects of a large interaction L'' are much alleviated owing to a characteristic dependence on the coupling parameter (Mf^2). For instance, the cross section of meson-nucleon scattering (L'' yields S-scattering only) is

$$d\sigma/d\Omega=[4\pi(Mf^2)^{-1}+A]^{-2} \quad (6)$$

(A = cut-off momentum), and the same factor appears in the expression for the two-nucleon potential (due to L''):

$$V(r)=-\tfrac{3}{4}[4\pi(Mf^2)^{-1}+A]^{-2}\mu r^{-2}|H_1{}^{(1)}(2i\mu r)| \quad (r\gg A^{-1}). \quad (7)$$

Dropping A in either (6) or (7) would lead to the results of fourth-order (static) perturbation theory. But since A is several times larger than $4\pi(Mf^2)^{-1}$ (taking $f\geqslant\mu$ and $A=M$), the actual values of both σ and $|V|$ are much smaller than expected from a perturbation treatment.[5] This may mean, of course, that the contribution of L' (4) are possibly of comparable magnitude. Indeed, the spin-dependent part of the nuclear forces[6] can only result from L' [granting (3)]. The same is true for the nonisotropic part of the pion-nucleon scattering (P-scattering). Last not least, it should be observed that the cross section (6) is independent of the mesonic and nucleonic charges, in other words: the scattering

would be the same in S states of isotopic spins $\frac{1}{2}$ and $\frac{3}{2}$, and there would be no charge exchange S-scattering; in disagreement with recent experimental findings.[7] It will, therefore, be a most crucial test for the pseudoscalar coupling theory whether, in a more complete treatment, it can account for the isotopic spin dependence (and the angular distribution) of the pion-nucleon scattering.

An encouraging feature is the saturation character of the nuclear forces arising from L'' (see reference 4), but here, too, the effects of L' will hardly be negligible.

If f turns out too large for treating L' as a perturbation, the transformations of Dyson and Foldy will be practically useless, and the mathematical problem posed by this theory will become very difficult.

[1] E. C. Nelson, Phys. Rev. **60**, 830 (1941); F. J. Dyson, Phys. Rev. **73**, 929 (1948); K. M. Case, Phys. Rev. **76**, 14 (1949).
[2] L. L. Foldy, Phys. Rev. **84**, 168 (1951).
[3] H. A. Bethe, Phys. Rev. **76**, 191 (1949).
[4] G. Wentzel, Helv. Phys. Acta **15**, 111 (1942); Prog. Theoret. Phys. **5**, 584 (1950), Sec. II.
[5] K. M. Watson and J. V. Lepore (Phys. Rev. **76**, 1157 (1949); see Figs. 2, 3 and 5) find that higher corrections to V, up to the eighth order (f^8), tend to increase the two-nucleon interaction. This is hard to reconcile with our qualitative argument.
[6] Unless other (heavier) mesons contribute to the forces.
[7] Fermi, Anderson, and Nagle, Phys. Rev. (to be published).

Low Temperature Thermal Expansion of Uranium*

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IN extending our studies of the elastic constants of uranium[1] a knowledge of the lengths of uranium rods at low temperatures appeared desirable. A dial gauge dilatometer was adapted to low temperature operation by immersing the end of the quartz tube containing the one-inch specimen in various refrigerants. Temperature of the specimen was measured with a copper-constantan thermocouple. Temperature gradients along the inner and outer quartz tubes were kept identical by filling the dilatometer with helium gas at about eight inches of mercury. A check run with a fused quartz rod was satisfactory in that the dial gauge reading remained constant. Another check run with oxygen-free high conductivity copper gave results (Fig. 1) in reasonable agreement with precision literature values,[2] after the necessary corrections had been made for the expansion of the fused quartz.[3,4]

On the other hand, the results obtained with coarse-grained uranium are quite unexpected in that the material expands upon cooling from the temperature of liquid nitrogen to that of liquid hydrogen. This behavior is reversible, and, as far as one can tell, there is no hysteresis. Final length readings are obtained within two or three minutes after changing the refrigerant, which is merely the time required for temperature equilibrium to be established. Similar results were obtained with three different specimens taken from a two-inch diameter casting along the directions shown in the figure. The casting had been annealed for six hours in the β-phase and was then cooled slowly to room temperature. There is a slight orientation effect, but it appears between room temperature and 75°K and is less than the experimental error at lower temperatures. The length changes shown in the figure have been reckoned from the room temperature (298°K) lengths of each specimen. This presentation increases the scatter of the low temperature points over what it would have been if all measurements had been referred to the 20°K lengths. Nevertheless, the increase in length of uranium upon cooling from liquid nitrogen to liquid hydrogen temperature is clearly shown.

One has to conclude that the inversion of thermal expansion corresponds to a density maximum. The present measurements do not give the complete thermal expansion curve below 60°K. However, an abrupt length and, hence, phase change appears unlikely on the basis of the specific heat measurements,[5] which indicate no transitions in this temperature range. Thus, one has to call on the anisotropy of uranium for a possible explanation of this anomalous behavior. X-ray observations indicate that uranium has a negative expansion coefficient for one crystal axis above room

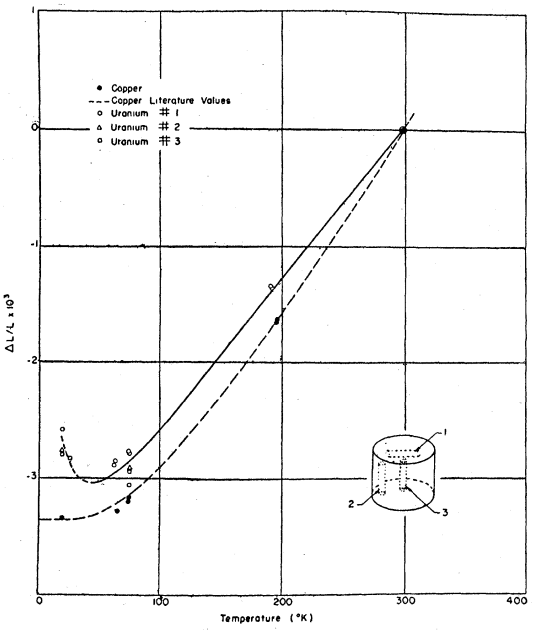

FIG. 1. Low temperature thermal expansion of uranium.

temperature,[6] and it might be that, at low temperatures, the negative expansion along this direction could become dominant in an aggregate of randomly oriented crystals. Further speculation on the nature of the anomaly will have to wait for more complete data on other physical properties.

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[1] Laquer, McGee, and Kilpatrick, Trans. Am. Soc. Metals **42**, 771 (1950).
[2] R. E. Gaumer and R. B. Scott, *The Thermal Expansion of Copper, A Literature Survey*, National Bureau of Standards Progress Report No. 2 for ONR Contract NAonr 12-48, pp. 26-29, January 13, 1949.
[3] K. Scheel and W. Heuse, Verhandl. deut. physik. Ges. **16**, 1 (1914).
[4] W. H. Keesom and D. W. Doborzyński, Physica **1**, 1089 (1934).
[5] Long, Jones, and Gordon, **20**, 695 (1952).
[6] J. J. Katz and E. Rabinowitch, *The Chemistry of Uranium* (McGraw Hill Book Company, New York, 1951), Part I, Chap. 5, National Nuclear Energy Series, Plutonium Project Record, Vol. 5, Div. VIII.

Calorimetric Determination of the Relationship between the Half-Life and Average Beta-Energy of C^{14}†

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CALORIMETRIC determinations have been made of the power generated by the beta-ray emission from samples containing measured amounts of carbon-14. The measured power per atom of C^{14} is equal to the product of the decay constant and the average beta-energy of C^{14}.

The calorimeter used was a modification of a liquid nitrogen calorimeter described by Cannon and Jenks.[1] The modified instrument operated at liquid helium temperatures and was considerably more sensitive than the liquid nitrogen calorimeter.