

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.<sup>7</sup> 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.

<sup>1</sup> E. C. Nelson, Phys. Rev. 60, 830 (1941); F. J. Dyson, Phys. Rev. 73, 929 (1948); K. M. Case, Phys. Rev. 76, 14 (1949).

<sup>2</sup> L. L. Foldy, Phys. Rev. 84, 168 (1951).

<sup>3</sup> H. A. Bethe, Phys. Rev. 76, 191 (1949).

<sup>4</sup> G. Wentzel, Helv. Phys. Acta 15, 111 (1942); Prog. Theoret. Phys. 5, 584 (1950), Sec. II.

<sup>5</sup> 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.

<sup>6</sup> Unless other (heavier) mesons contribute to the forces.

<sup>7</sup> 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<sup>1</sup> 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,<sup>2</sup> after the necessary corrections had been made for the expansion of the fused quartz.<sup>3,4</sup>

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  $\beta$ -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,<sup>5</sup> 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

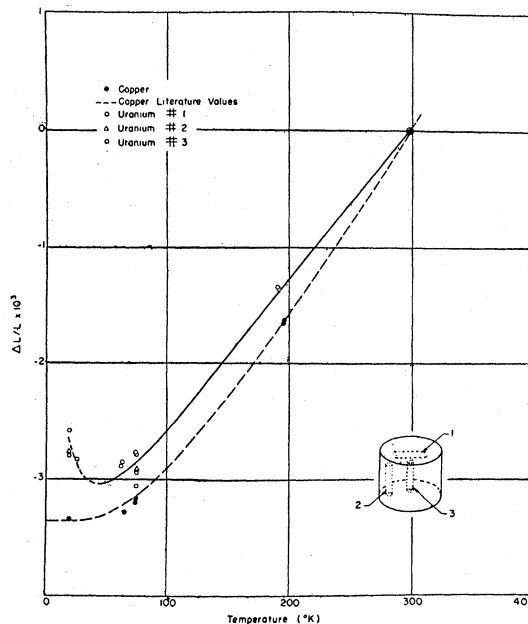


FIG. 1. Low temperature thermal expansion of uranium.

temperature,<sup>6</sup> 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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<sup>1</sup> Laquer, McGee, and Kilpatrick, Trans. Am. Soc. Metals 42, 771 (1950).

<sup>2</sup> 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 NAnr 12-48, pp. 26-29, January 13, 1949.

<sup>3</sup> K. Scheel and W. Heuse, Verhandl. deut. physik. Ges. 16, 1 (1914).

<sup>4</sup> W. H. Keesom and D. W. Dobrzyński, Physica 1, 1089 (1934).

<sup>5</sup> Long, Jones, and Gordon, 20, 695 (1952).

<sup>6</sup> 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.<sup>1</sup> The modified instrument operated at liquid helium temperatures and was considerably more sensitive than the liquid nitrogen calorimeter.