It is more convenient to carry out the summation over the unoccupied states for which Eq. (2) is applicable. According to Eqs. (2) and (4), $v_x=(\hbar/m^*)l_x$, so that

$$P_x'=m^*\Sigma_u v_x.$$

Replacing $\Sigma_u v_x$ by means of Eq. (3), one obtains

$$P_x'=-(m_{\text{eff}}/e)j_x, \tag{8}$$

where $m_{\text{eff}}=-m^*$ is the effective mass of electrons for which the energy levels are given by Eq. (2). Equation (8) for P_x' resembles Eq. (6) for P_x except that the electron mass is replaced by the effective mass, and since m_{eff} is negative P_x' is in the same direction as j_x.[8] The use of the crystal momentum P_x' instead of the actual momentum P_x in the conservation conditions for the coil employed by Brown and Barnett would seem to account for the remarks in their paper that the writer considers misleading.

Electron-inertia experiments do not reveal the energy levels in metals. This is consistent with the modern theory of solids and in particular with the accepted explanation for positive Hall coefficients.

[1] Sheldon Brown and S. J. Barnett, Phys. Rev. **87**, 601 (1952).
[2] R. Peierls, Z. Physik **53**, 255 (1929).
[3] See, for example, *International Critical Tables* **6**, 416 (1929); I. K. Kikoin, Physik. Z. Sowjetunion **9**, 1 (1936); Pugh, Rostoker, and Schindler, Phys. Rev. **80**, 688 (1950); J. P. Jan and H. M. Gijsman, Physica **5**, 277 (1952).
[4] C. G. Darwin, Proc. Roy. Soc. (London) **A154**, 61 (1936).
[5] N. F. Mott and H. Jones, *The Theory of the Properties of Metals and Alloys* (Clarendon Press, Oxford, 1936).
[6] The symbol "e" as employed in this note represents the magnitude of the electronic charge.
[7] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, New York, 1950).
[8] See, for example, N. Rostoker, Am. J. Phys. **20**, 100 (1952), where this point is discussed in detail. (The term "momentum" in that paper should be replaced by "crystal momentum" in order to be consistent with present terminology.)

Interpretation of e/m Values for Electrons in Crystals

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A RECENT investigation[1] by Brown and Barnett of e/m for electrons in molybdenum and zinc by an inertial method has shown that the charge to mass ratio is that of an electron. It is the purpose of this letter to point out that this is the result expected from the theory of electronic conductivity; the new and precise experimental results are in excellent agreement with the theory and do not require any modification of the interpretation of the anomalous or positive Hall effect.

The paradox that e/m is negative in the Brown-Barnett experiment and positive in the Hall effect experiment is due to the fact that two different meanings m_B and m_H should be associated with the symbol m.

The fact that m_B should be taken as the electron mass follows at once from the theory of both holes and electrons in semiconductors and for electronic conduction in general.[2] In fact, the current due to "positive carriers" or "holes" is simply a shorthand way of dealing with the combined actions of many electrons. Hence, the ratio of current density to momentum density is simply $-e/m$, where $e=|e|$ is the electronic charge and m the electronic mass.[3]

On the other hand, if one could view the behavior of an isolated hole in a semiconductor under the influence of electric and magnetic fields, one would conclude that its behavior was that of a particle of charge $+e$ and a positive mass.[4] The behavior of small groups of holes introduced by light or injection in germanium has, furthermore, put these theoretical conclusions on a sound operational footing.[5]

Certain other consequences of the theoretical model show, however, that the hole should not be considered to have positive mass. For example, one readily concludes that if the mass of a natural and perfect germanium crystal is M, then adding one electron gives it a mass $M+m$ and adding one hole $M-m$. The weights and momenta of the crystal will be consistent with these masses. Evidently, a gravitational field exerted on a stationary crystal will cause electrons to be drawn downwards and holes upwards.

An electron (respectively, hole) wave packet moving in a stationary crystal with group velocity v_g imparts a momentum mv_g (respectively, $-mv_g$) to the system. Thus, upon collision with phonons, a hole transfers momentum to the rest of the system as if it had a negative mass.

The consequences discussed above arise simply from the fact that conduction by both "excess electrons" and "holes" is really produced by electrons. The magnitude of the effective mass to use in conductivity theory depends on more complicated aspects of the interaction of the electron waves and the crystal. It is highly probable, for example, that the "effective masses" for electrons and holes in germanium cannot be described by one number each but must be regarded from a much more sophisticated viewpoint.[6]

[1] Sheldon Brown and S. J. Barnett, Phys. Rev. **87**, 601 (1952).
[2] This general conclusion has been expressed by C. G. Darwin, Proc. Roy. Soc. (London) **A154**, 61 (1936).
[3] For the case of one hole, this follows directly from Eqs. (2) and (3) on page 179 of W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950).
[4] Negative charge and negative mass do not lead to sensible results as is shown in reference 3, p. 181.
[5] See reference 3 for references to the literature and also W. Shockley, Phys. Today **3**, 16 (1950).
[6] See, for example, reference 3, p. 341.

Optical Properties of Crystalline Thoria

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THE optical properties of fused transparent crystalline thoria have been investigated. Spectroscopic analysis of the crystals showed that their purity is comparable to that of mantle grade thorium nitrate and standard thorium metal. The purity is estimated to be in the vicinity of 99.9 percent. Rather complex changes of the absorption spectrum could be observed when the specimen was heated in vacuum, oxygen, or hydrogen. Figure 1 shows the absorption spectrum (uncorrected for reflection) of a thoria crystal, which has been taken through the following cycle: (a) heating to 1800°C in vacuum, (b) heating to 1000°C in air, (c) heating to 1000°C in vacuum, (d) reheating in vacuum at 1800°C.

Heating in oxygen or air reddens the crystal and following heating in vacuum or hydrogen at 1000°C results in bleaching. The ultraviolet cutoff for these states is at 3700A. This fundamental absorption may be associated with the gap between the filled band and conduction band. The change of the absorption

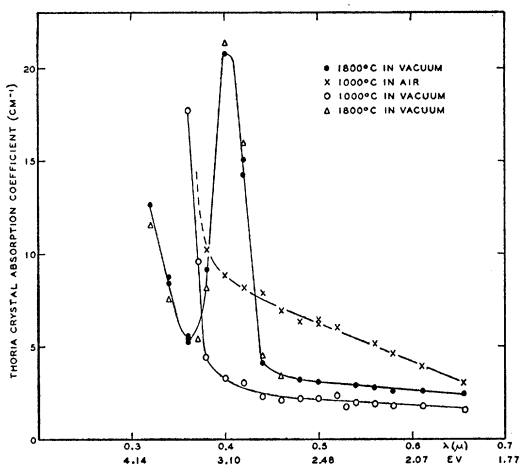

FIG. 1. Optical absorption of crystalline thoria.

curve following the heating to 1000°C in vacuum (curves *a* or *d* in Fig. 1) is characterized by: (1) a shift in the ultraviolet cutoff from about 3700A to 3200A, and (2) the appearance of a sharp absorption peak at about 4000A.

Tentatively, we relate this absorption peak to the presence of excess thorium (oxygen deficiency) of the specimen. Consistent with this hypothesis are weight changes, which are found when alternating the 1000°C oxygen and 1800°C vacuum treatment. The weight changes account for intake or release of approximately 10^{18} oxygen atoms per cc. The weight changes have been checked by gas analysis. No measurable weight changes, however, could be found, when the 1000°C oxygen and 1000°C vacuum treatment were alternated. We refer to these crystals as oxygen-rich. Oxygen-rich crystals bleached in vacuum or hydrogen turn red when exposed to light in the region just beyond the cutoff. The trapping centers for the radiation-produced reddening are shallow; bleaching occurs at 200°C in vacuum.

Another variety of color is obtained by rapid quenching which results in a deep black color. These crystals are opaque in the measured spectral range from 0.2 to 2μ.

No photoconductivity has been observed for any of the described crystals at light intensities, where that of diamond is easily detected.

Measurements pertinent to the mechanism of electrical conductivity of oxygen-poor thoria specimens have been recently published.[1] In this case part of the current is electrolytic, causing rapid decomposition of the crystal. Measurements of electrical conductivity with oxygen-rich crystals were made at 1100°C in oxygen of atmospheric pressure. In contrast to the oxygen-poor specimen, no electrolytic decomposition is detected.

It is a pleasure to acknowledge the services of Harry Bleecher, who developed the necessary polishing techniques and prepared the specimens.

[1] W. E. Danforth, Phys. Rev. **86**, 416 (1952).

Evidence for a New Level in Be^7

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THE study of the energy levels of mirror nuclei is one of the most effective ways of testing the hypothesis that proton-proton and neutron-neutron forces are equal in the low energy region. In several cases it has been possible to demonstrate very close similarities between the level spectra of mirror nuclei and also to account fairly well for the apparent differences in excitation of corresponding levels.[1–4]

In the case of the mirror nuclei Li^7 and Be^7 the correspondence of the ground states and first excited states is already well established,[5] and there is some evidence that there are levels in Li^7 corresponding to levels at about 6.4 and 7.3 Mev in Be^7.[6] Franzen and Likely[7] were probably not able to observe the 7.54-Mev level in Li^7 by the inelastic scattering of protons on Li, since the protons coming from a (p, pn) reaction produced too much background at that energy. Recently a new level has been found[8,9] in Li^7 at 4.62 Mev. The corresponding region of excitation in Be^7 has not previously been adequately explored, and it was therefore of some interest to discover whether or not there is a mirror level.

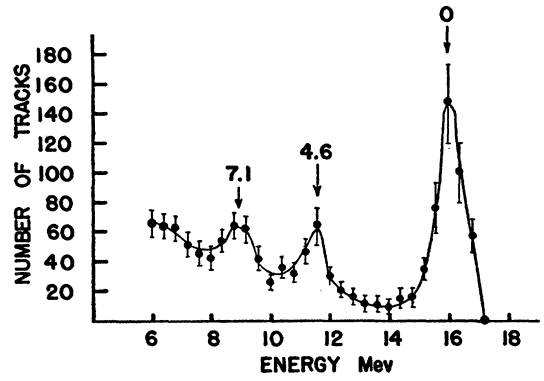

FIG. 1. Neutron spectrum from Li$^7(p, n)$Be^7 at 16°, corrected for escape and for the variation of $n-p$ cross section (about 1000 tracks; bombarding energy = 18.2 Mev).

In the present work 18.3-Mev protons from the external beam of the Princeton cyclotron bombarded natural metallic lithium targets 0.006 in. in thickness. Neutrons produced by the reaction Li$^7(p, n)$Be^7 were detected at 16° and 60° to the incident beam by the proton recoils they produced in Eastman Kodak NTB emulsions of 200-microns thickness. Tracks were accepted up to angles of 15° in the neutron direction in the plane of the emulsion and up to about 11° in dip. About 1000 tracks were counted at each angle. The neutron spectrum at 16°, suitably corrected for the escape of long tracks and for the energy dependence of the neutron-proton scattering cross section, is shown in Fig. 1. Besides the ground-state group which also includes the transitions to the first excited state at 0.43 Mev which could not be resolved and a continuous background probably due mainly to three-body breakup of the compound nucleus, the spectrum shows evidence for excited states in Be^7 at 4.6 Mev and 7.1 Mev. The spectrum obtained at 60° showed the same groups with energies consistent with their arising from the Li$^7(p, n)$Be^7 process. The 7.1-Mev level can be identified with that found from proton scattering on Li^6,[6] and the 4.6-Mev level as the mirror of the 4.62-Mev level in Li^7.

The energy of the new level in Be^7 cannot be determined very accurately from the data. The range energy relation in nuclear emulsions depends somewhat on the humidity of the atmosphere in which they are exposed, and in this work the energy of the ground state group at 16° was calculated and used to determine one fixed point on the range-energy relation; the rest of the curve being assumed to have the same shape as that used by Richards *et al.*[10] Since the ground-state group is composite and the relative strength of the two components is not known, it is possible that an error of up to 200 kev may be introduced into the estimate of the energy of the excited level. The best estimate that can be given for the excitation energy is therefore 4.6±0.2 Mev. Within the somewhat large experimental error, this is the same as the excitation of the corresponding level in Li^7. No useful comparison of the energies of the two levels can be made until the energy of the Be^7 level is known with greater precision.

I am greatly indebted to Professor P. C. Gugelot for his advice on this problem and to Mrs. L. Anderson for reading the plates. This work was supported by the AEC and the Higgins Scientific Trust Fund.

[1] R. A. Laubenstein and M. J. W. Laubenstein, Phys. Rev. **84**, 18 (1951).
[2] V. R. Johnson, Phys. Rev. **86**, 302 (1952).
[3] R. G. Thomas, Phys. Rev. **81**, 148 (1951).
[4] R. G. Thomas, Phys. Rev. (to be published).
[5] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951).
[6] S. Bashkin and H. T. Richards, Phys. Rev. **84**, 1124 (1951).
[7] W. Franzen and J. G. Likely, Phys. Rev. **87**, 667 (1952).
[8] H. E. Gove and J. A. Harvey, Phys. Rev. **82**, 658 (1951).
[9] Gelinas, Class, and Hanna, Phys. Rev. **83**, 1260 (1951).
[10] Richards, Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **83**, 994 (1951).

T-Tracks in Nuclear Emulsions*

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IN emulsions exposed[1] for about 5 hours at 15 g/cm^2 and geomagnetic latitude 41°N, we have observed examples of novel but puzzling events which we call *T*-tracks. A *T*-track appears as a black track with its last grain crossed by a straight thin track, the last grain being at the end of the dense track corresponding to the end of travel of the heavily ionizing particle, which we call