related to a change in the thermal activation energy of the semiconductor due to the applied pressure.

If the activation energy calculated for the various pressures is plotted against the dilatation, $\Delta V/V$, a straight line is obtained, provided the value of activation energy of 0.38 ev found from Hall effect measurements by Johnson[3] is used for the value at zero pressure.

From the graph it is found that

$$\Delta E/(\Delta V/V)=0.041 \text{ ev per one percent dilatation.}$$

Photo-conductive films of tellurium have been prepared by the author, and from measurements of the spectral distribution of sensitivity, a value of the optical activation energy can be obtained. It was found that for different layers the sensitivity fell to half-value at wave-lengths in the range 3.2μ to 3.5μ, corresponding to an optical activation energy of 0.35 to 0.38 ev. There is thus good agreement between the optical and thermal activation energies.

It has also been observed that the "threshold" wave-length of sensitivity is temperature dependent, moving to longer wave-lengths on cooling, and the extent of the shift has now been measured. Unfortunately the sensitivity of tellurium cells falls rapidly with increasing temperature, and in general spectral sensitivity measurements cannot be carried out much above 150°K. However, fairly good results were obtained on two cells from 77°K to 161°K and 77°K to 195°K respectively. The observed shifts of 0.16μ and 0.20μ, give an energy change:—

$$\Delta E/\Delta T=2.1\times10^{-4} \quad\text{and}\quad 1.9\times10^{-4} \text{ ev/°C}.$$

As a result of the restricted temperature range, the accuracy is not high, but a mean value of $\Delta E/\Delta T=2\times10^{-4}$ ev/°C may be taken. Since the thermal expansion coefficient, $\Delta V/V\cdot\Delta T=51\times10^{-6}$/°C, we obtain from the optical measurements, $\Delta E(\Delta V/V)=0.04$ ev per one percent dilatation.

This figure is almost identical with that calculated from the pressure measurements. Such close agreement is fortuitous, but we may conclude that within the accuracy of the measurements the values of the energy change with dilatation are the same in the two cases. The energy gap is thus determined primarily by the volume, the forbidden zone decreasing in width as the atoms move closer together. Bardeen has suggested that the opposite effect occurs in germanium.

An interesting conclusion to be drawn from the above results is that a film of tellurium operated at 20,000 kg/cm² and suitable low temperature, should be photo-conductive at wave-lengths $\sim12\mu$.

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Boride Cathodes

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THE thermionic emission properties of the borides of the alkaline-earth and rare-earth metals and thorium have been investigated. These compounds all have the same formula MB_6 and the same crystal structure consisting of a three-dimensional boron framework in whose interlattice spaces the metal atoms are embedded. The valence electrons of the metal atoms are not accepted by the B_6 complex, thus giving rise to the presence of free electrons which impart a metallic character to these compounds.

This is evident from their high electrical conductivity. Lanthanum boride, for example, has a specific resistance of 27 μohm-cm at room temperature and a positive resistance-temperature coefficient of 0.071 μohm/°C. Hall effect measurements on sintered lanthanum boride show approximately one free electron per lanthanum atom. The strong binding forces between the boron atoms lead to a series of compounds which are very refractory, with melting points above 2100°C. The hexaborides are also very stable chemically; moisture, oxygen and even hydrochloric acid do not react with them.

When this structure is heated to a sufficiently high temperature, the metal atoms at the surface evaporate away. They are, however, immediately replaced by diffusion of metal atoms from the underlying cells. The boron framework does not evaporate but remains intact. This process gives a mechanism for constantly maintaining an active cathode surface. This feature, together with the high electrical conductivity and high thermal and chemical stability, gives ideal properties for a cathode material.

Thermionic emission measurements show the rare-earth metal borides to be superior to the others. The emission constants obtained from Richardson plots for the hexaborides are shown in Table I. Lanthanum boride gave the highest emission and was found to have a relatively low evaporation rate corresponding to a latent heat of evaporation of 169 kcal./mole.

TABLE I. Hexaboride electron emission constants determined for Dushman's equation.

Boride	A	ϕ
CaB_6	2.6 amp./cm²/deg. K²	2.86 volts
SrB_6	0.14	2.67
BaB_6	16	3.45
LaB_6	29	2.66
CeB_6	3.6	2.59
ThB_6	0.53	2.92

Boride cathodes require no special activation. When they are heated for a few minutes at 1400°C to 1600°C for outgassing, they are found to be completely active. When lanthanum boride is bombarded with mercury ions which exceed energies of approximately 20 ev lanthanum atoms are readily sputtered off the surface making the cathode inactive. However, at 1400°C, the lanthanum atoms diffuse rapidly to the surface, making the cathode active again.

The pulsed emission is the same as the d.c. emission for the boride cathodes.

If these cathode materials are operated in contact with the refractory metals, the boron atoms diffuse into their metal lattices forming interstitial boron alloys with them. When this occurs, the boron framework which holds the alkaline-earth or rare-earth metal atoms collapses, permitting them to evaporate. The hexaborides may be operated in contact with tantalum carbide or carbon.

On the Spins of Li^6 and B^{10}

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IT was pointed out by Feenberg[1] that according to the p^n shell model, the spins of Li^6 and B^{10} are one in *LS* coupling, but three in *jj* coupling; it was therefore natural to ask if the different spins of these two nuclei can be explained by intermediate coupling. Calculations are in progress on this subject, and the first results are very satisfactory.[2]

In the meantime it has been suggested by Inglis, Mayer, and Kurath[3] that the coupling should be extreme *jj* and the mixture of exchange forces should be such as to give the correct spins for Li^6 and B^{10}. We wish to discuss now some consequences of this hypothesis.

Since the configuration $p_{\frac{3}{2}}^6$ is the almost closed shell corresponding to $p_{\frac{3}{2}}^2$, the relative positions of the levels will be the same in the first approximation, and an inversion can take place only if there is degeneracy in the first approximation.

If we assume for the nuclear interaction the expression

$$-[(1-m-b-h)+mP_x+bP_\sigma+hP_xP_\sigma]J(r), \tag{1}$$

the energy difference between the levels with $I=1$ and $I=3$ has the same sign as $m+b$, and the condition for the degeneracy in the first approximation is

$$m+b=0. \tag{2}$$

In order to obtain the difference E_1-E_3 in the second approximation, we calculated the transformation matrix from LS to jj coupling by diagonalizing the matrix of spin-orbit interaction,[2] and then transformed the matrix of nuclear interaction[4] to the jj scheme and calculated the second approximation by the ordinary formulas.

The result is

$$E_1-E_3=-15F_2^2/\alpha \quad \text{for } p_{\frac{3}{2}}^2, \tag{3}$$

and

$$E_1-E_3=-15(F_2^2/\alpha)+(40/9\alpha)[m(F_0-5F_2)-3(h-m)F_2]^2 \quad \text{for } p_{\frac{3}{2}}^6, \tag{4}$$

where $\alpha=-\frac{1}{2}\zeta$ is the (positive) parameter of spin-orbit coupling, and F_0 and F_2 are the (generalized) parameters of Slater.

We see therefore that (2) is sufficient to give the correct spin for Li^6 in extreme jj coupling, but the correct spin of B^{10} can be obtained only by an appropriate choice of m and h.

If we remember that[5]

$$q=1-2b-2h\approx 0.6, \tag{5}$$

we obtain from (2) that

$$h-m\approx 0.2. \tag{6}$$

Introducing this value into (4) we see that the correct spin of B^{10} cannot be obtained on the hypothesis of Inglis[3] that $m=b=0$, nor on the hypothesis of Mayer[6] that $J(r)=\delta(r)$, from which it follows that $F_0=5F_2$.

Only an interaction of finite range, with a strong Majorana component opposed by an equally strong Bartlett component, and also accompanied by a stronger Heisenberg component, can explain the spins of Li^6 and B^{10} in extreme jj coupling. It is rather doubtful whether such an interaction corresponds to reality.

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Neutral Impurity Scattering in Semiconductors

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A THEORY of the scattering of conduction electrons in a semiconductor by ionized impurity centers was recently proposed by Conwell and Weisskopf.[1] Another important source of resistivity at low temperatures is the scattering due to neutral impurity atoms which must be considered particularly in the case of semiconductors showing a small degree of ionization. Pearson and Bardeen[2] have pointed out that the theoretical treatment of the problem should be similar to the scattering of slow electrons by hydrogen atoms, and have shown by approximate calculations that the effective scattering cross sections of ionized and neutral impurities are comparable at temperatures of the order of 100°K. In this letter we suggest a more exact solution of the problem, using the results of Massey and Moiseiwitch's recent work[3] on the slow collisions of electrons and hydrogen atoms.

For small incident velocities the scattering is spherically symmetrical and only the zero-order phase angle[4] need be considered. Thus the differential cross section of scattering is reduced to

$$I_0(\theta)=(1/k^2)\sin^2\eta_0 \tag{1}$$

where η_0 is the zero-order phase angle, θ is the angle of scattering, k is $2\pi mv/h$, and v is the velocity of the incident electron. In a semiconductor the orbit of the bound electron or hole about the corresponding ion (i.e., the equivalent of the Bohr radius in an hydrogen atom) is given by

$$a_0=\kappa h^2/4\pi^2me^2 \tag{2}$$

where κ is the effective dielectric constant.

η_0 has been calculated by McDougall[5] by numerical integration for different values of ka_0, using the static field of the hydrogen atom. The complete solution, however, must include the electron exchange effects (which are particularly important for slow electrons), and also the effect of the polarization of the atom by the incident electron.

In their recent work Massey and Moiseiwitsch,[3] using Hulthén's variational method have included both these effects. It may be seen from their Fig. 1(d) that the dimensionless quantity

$$k^2Q_0=2\pi k^2\int_0^\pi I_0(\theta)\sin\theta d\theta=4\pi\sin^2\eta_0 \tag{3}$$

is proportional to ka_0 for a wide range of incident velocities. Q_0 is the zero-order partial cross section. Up to $ka_0=0.5$ (i.e., incident energies of up to 25 percent of the ionization energy) an analytical expression of the form

$$k^2Q_0=20ka_0 \tag{4}$$

may be used as a good approximation.

In determining the resistivity it is useful to introduce τ, the relaxation (or collision) time; $1/\tau$ may be considered as the total scattering probability. It is related to the differential cross section by the expression

$$1/\tau=N_nv\int_0^\pi 2\pi I_0(\theta)\sin\theta(1-\cos\theta)d\theta \tag{5}$$

where N_n is the concentration (per cm³) of neutral impurities.

With substitution for $I_0(\theta)$ from Eq. (1) this integral gives

$$1/\tau=N_nv(4\pi/k^2)\sin^2\eta_0=N_nvQ_0. \tag{6}$$

Combining with the Eq. (4) and using $a_0=\kappa h^2/4\pi^2me^2$ and $k=2\pi mv/h$ we obtain

$$1/\tau=20\kappa N_nh^3/8\pi^3m^2e^2. \tag{7}$$

The significance of this result is that τ is independent of the velocity of the electrons. In Conwell and Weisskopf's case τ is seen to vary as v^3.

The expression for the resistivity is easily obtained from Eq. (7)

$$\rho_n=m/ne^2\tau=20\kappa N_nh^3/8\pi^3nme^4 \tag{8}$$

where n, e and m are the concentration, charge and effective mass of the conduction electrons (or holes) respectively.

Expressing ρ_n in ohm-cm and substituting for the constants we obtain

$$\rho_n=4.35\times10^{-4}\kappa N_n/n \text{ ohm-cm.} \tag{9}$$

TABLE I. Comparison of ρ_n and ρ_i calculated for Pearson and Bardeen's silicon samples 2 and B (reference 2). $N_{\text{total}}=N_n+N_i$ (cm⁻³); ρ_n and ρ_i in ohm-cm.

$1/T$	Sample 2 ($N_{\text{total}}=6\times10^{17}$)			Sample B ($N_{\text{total}}=1.25\times10^{18}$)		
(°K)⁻¹	$n(=N_i)$	ρ_n	ρ_i	$n(=N_i)$	ρ_n	ρ_i
12×10^{-3}	3.7×10^{16}	0.0866	0.0526	5.3×10^{17}	0.0077	0.0283
12×10^{-3}	7.4×10^{16}	0.0402	0.0390	5.3×10^{17}	0.0077	0.0250
6×10^{-3}	2.37×10^{17}	0.0086	0.0194	7.4×10^{17}	0.0031	0.0155
5×10^{-3}	3.3×10^{17}	0.0046	0.0153	8.25×10^{17}	0.0029	0.0129