Again, taking the properties of the lowest state as indicative of the properties of the crystal at moderate temperatures, we ask if the state of large crystal spin is lowest when the spin is in the principal plane, and when it is perpendicular to that plane (parallel to the principal axis). With the spin in the crystal plane, the states of lowest spin-orbit energy have charge distributions largely outside the principal plane, so that the overlapping of the wave functions is small near most of the next nuclei and the exchange integrals probably positive, making also the electrostatic energy low for the states of large total spin. In this direction, then, we expect ferromagnetism. With the spin perpendicular to this plane, the state with lowest spin-orbit energy has charge distribution in the plane of the nearest neighbors, so is apt to have negative exchange integrals; the state which probably has positive exchange integrals has orbital momenta in the principal plane and so high spin-orbit energy. It has energy lower than the state with spin in the principal plane only when the external field is extremely high; hence the difficulty of magnetization along the axis, as observed in pyrrhotite.

This is an example of the fact that ferromagnetic anisotropy, and consequently remanence and hysteresis, always seem to arise from the spin-orbit interaction within the atoms.

It will be noted that this type of ferromagnetism depends largely on the orientation of the orbits. The spins in this model are, as usual, coupled together by the electrostatic exchange effect consequent upon the exclusion principle. The orbits are coupled to one another through the medium of the spins, there being no direct exchange coupling of the orbits.

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Photoelectric Properties and Electrical Resistance of Metallic Films

Recently completed experiments[1] show that a film of spectroscopically pure, outgassed cadmium deposited by evaporation on an oxidized iron plate in vacuum does not, at any stage in the formation of the film, exhibit a threshold wave-length longer than that characteristic of the cadmium in bulk. This is true for temperatures of the cathode between liquid air and room temperature. Similar results have been reported for mercury.[2] As is well known, thin films of the alkali metals show a marked dependence of the threshold wave-length and photoelectric emission on film thickness. Films of platinum, silver and gold also exhibit maxima in their total emission-thickness curves. Since these effects are observed for film thicknesses of less than about 20 molecular layers, the failure to observe them with cadmium and mercury films can be explained by supposing that it is impossible to form truly thin films of these two metals under ordinary conditions of deposition.

To test this supposition, we have attempted to gain some information concerning the structure of cadmium films by investigating the relation between their electrical resistivity and thickness. In the initial experiments the cadmium was condensed in vacuum on a glass plate at room temperature, and resistance measurements were made while the film was being driven off by warming the plate with a heating coil. The resistivity-thickness curve was found to be of the same general type as those that have been reported for many other metals; that is, as the average thickness of the film decreases, the resistivity increases from the value characteristic of the metal in bulk, at first slowly and then more rapidly, and finally, just beyond a so-called "critical thickness," rapidly approaches an infinite value.

Our initial experiments showed the critical thickness for cadmium to be not less than $200\text{–}300\times10^{-7}$ cm. In making this calculation, we estimated the value of the resistivity at the critical thickness to be twice that of the bulk metal. Experiences of various workers with other metals indicate that this assumed value is probably too small, and hence that the foregoing values for the critical thickness are smaller than the actual one.

To determine the critical thickness by a method not involving any assumption about the resistivity, the remaining experiments were made with a molecular beam apparatus, in which cadmium vapor effused through a pinhole from a vessel containing the vapor at a known pressure and deposited on a plate cooled by liquid air. The thickness of the deposit could be calculated from the vapor pressure and the geometry of the apparatus. The apparatus did not differ essentially from that used by Brady in photoelectric experiments[3] except for the use of a glass depositing surface equipped with a pair of tungsten electrodes and the addition of a magnetically-operated glass shutter placed in front of this surface; the purpose of the shutter was to shield the central portion of the surface from the cadmium beam during the time that thick cadmium terminals were being deposited over the tungsten wires and also while temperature equilibrium was being established in the apparatus.

Although measurements with this apparatus were disturbed because the electric current passing through the film tended to destroy the conductivity, enough data were obtained to place the value of the critical thickness of cadmium at 1800 molecular layers or about 400×10^{-7} cm. The total error in this determination may be as much as 25 percent. Now mercury, which also fails to exhibit photoelectric properties that are peculiar to the thin-film stage, has a critical thickness[4] of $200\text{–}300\times10^{-7}$ cm. On the

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[1] J. Schmidt, R. F. Hughes, Helen Webb, Alice Hartley and D. Roller, unpublished.

[2] D. Roller, W. H. Jordan and C. S. Woodward, Phys. Rev. **38**, 396 (1931).

[3] J. J. Brady, Phys. Rev. **41**, 613 (1932).

[4] W. Braunbek, Zeits. f. Physik **59**, 191 (1930).

other hand, the published data on rubidium[5] indicate that its critical thickness is only about 8 or 10 times greater than the thickness for which the photoelectric threshold wave-length is a maximum; that is the critical thickness is less than 10×10^{-7} cm. Furthermore, the literature shows that the critical thicknesses of platinum, silver and gold are less than 5×, 20×, and 8×10^{-7} cm, respectively. Of the metals studied, then, the only ones which do not exhibit thin-film photoelectric anomalies are also the only ones which have a large critical thickness.

Such a correlation is to be expected. Most of the theories which have been advanced to account for changes in resistivity of metallic films with thickness involve the idea that the molecules, either before or after striking the depositing surface, group together into clusters, so that a comparatively large amount of material must be deposited to fill the gaps between clusters and thus render the film conducting. The larger the number of molecules in the clusters, the larger is the amount of material which must be deposited to establish conductivity; that is, the larger is the critical thickness. It seems reasonable to suppose that if a thin-film photoelectric effect is observed for one metal and not for another, it is because the first metal deposits more uniformly than does the second metal. When the surface area of metal exposed to the radiation has become large enough to give a measurable photoelectric current, or possibly when the particles of metal have finally established good electrical contact with the underlying iron surface, the actual thickness of the first metal film is still of molecular dimensions whereas that of the second metal film, due to the larger constituent particles, is of macroscopic dimensions. On this view, a dependence of photoelectric properties on film thickness will be observed only for metal films whose constituent particles, as indicated by the critical thickness, are small.

We wish to thank Miss Mary Louise Kropp and Mrs. Edith Townes for their invaluable assistance in the experimental work, and Mr. F. W. Crawford for his help in constructing parts of the apparatus. The spectroscopically pure cadmium used in this work was obtained through the generosity of the New Jersey Zinc Company.

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December 18, 1933.

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[5] H. E. Ives and A. L. Johnsrud, Astrophys. J. **62**, 309 (1925).

Polarization of Fluorescence Radiation

The following problem has been investigated with the aid of the Dirac theory of light quanta. Light from a radiator falls upon a scattering atom in the ground state α_0 and raises the atom to the state γ from which it may fall to another, say a metastable level through an intermediate state β, emitting successively the light quanta ρ and δ. The intensity of the fluorescence radiation ρ polarized in a given direction was examined, taking into account the possibility of hyperfine structure and the effect of applying a magnetic field to the scatterer.

The result is found to be independent of the damping constant of the lower level β, only the damping constant Γ of the upper level γ entering into the final result. The formulae for the degree of polarization and the intensity of the scattered fluorescence radiation are therefore the same as those given by Breit for the case of resonance radiation.[1]

One may understand this result by observing that if the intermediate level β were metastable, then the polarization of the radiation emitted in the transition γ to β would depend on the interference of coherent transitions due to the atom coming back to the same sublevel of β. The effect of radiation is to broaden each sublevel of β into a band. Transitions to the same energy value in a given band may be regarded as giving rise to coherent radiations. The width of the band is however immaterial for the polarization of the fluorescence radiation.

This result is to be contrasted with that for the breadth of the line emitted in the transition γ to β, which as is known,[2] is equal to the sum of the breadths of the two levels.

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December 22, 1933.

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[1] G. Breit, Rev. Mod. Phys. **5**, 91 (1932). Eqs. (159), (164).

[2] Weisskopf and Wigner, Zeits. f. Physik **63**, 54 (1930)