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Field Emission from Photoconductors

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Field emission current was drawn from sharp needles of the photoconductors CdS and CdSe. It increased greatly when light that excited photoconductivity was incident on the emitting area. Possible mechanisms are mentioned.

FIELD emission from metals has been rather thoroughly studied. Mueller's[1] electron projection microscope, for example, has afforded a particularly elegant approach to the problem. In contrast, little is known about field emission from semiconductors, although one would expect several new effects to appear. This note reports briefly on one of these—an unusual phenomenon that occurs when field emission is drawn from a photoconductor like CdS.

In our experiments, single-crystal needles of CdS (or CdSe) were mounted in a Mueller-type electron projection tube. They were sharpened by electron bombardment from a surrounding W wire loop. The CdS points reached temperatures above 500°C, as judged by the shift in the fundamental optical absorption edge. The lower parts of the needles were cooler. Sharpening apparently occurred by preferential evaporation.

Smooth points were very rarely obtained. Projection patterns characteristic of lattice symmetry were therefore extremely difficult to observe. Nevertheless, the emission had an interesting characteristic not found for metals or other substances of high conductivity: it was extremely sensitive to radiation that excited photoconductivity in the CdS.

In a particular case, 12 kv could be applied to the transparent anode[2] in the dark without producing a field emission of more than 10^{-8} ampere. When a small spot of light (from a 2-watt Western Union zirconium arc) was focused on the tip of the CdS needle, however, more than 10^{-5} ampere could be drawn at 6 kv. Internal reflections and scattering of light over large distances in the crystal were prevented by introducing a filter that passed only wavelengths below 500 mμ, well within the fundamental absorption band of CdS. It was then apparent that the effect occurred only when the emitting area was irradiated. With light incident from one side, the illuminated half of the point emitted preferentially.

In one case, two points emitted current. One was on the side of the needle near the middle; the other was at the tip. Currents over 10^{-5} ampere could be drawn from either point alone by irradiating it with the blue light for which CdS is opaque. As judged by projection patterns, the potential distribution along the needle changed radically when the light spot was shifted. In tubes with phosphor coatings, images could be observed at very low current levels, and there was evidence that the potential distribution around the needle tip changed under illumination.

Several factors may be involved in these effects. One of them is simply the spreading resistance associated with the emission of field currents through a needle tip only a micron or thereabouts in diameter. This resistance R is of order $k\rho/d$, where ρ is the resistivity, d is the tip diameter, and k is a geometrical constant of order 10. In the dark, ρ for CdS may be $>10^7$ ohm cm. With $d\sim 10^{-4}$ cm, R may be $>10^{12}$ ohms. Thus, even when the field current in the dark is less than 10^{-8} ampere, several thousand volts may be lost in the needle resistance instead of appearing in the vacuum. When the needle is illuminated, the CdS resistance decreases, the voltage appears in the vacuum, and the field emission accordingly goes up.

Another important influence has been pointed out to us by M. H. Hebb. The equipotential surfaces in the vacuum at the end of the needle have a smaller curvature than the surface of the needle tip itself because of the current flow through the high resistance of the needle material. Hebb's calculations show that these departures become very important when the voltage drop in the spreading resistance is an appreciable fraction of the applied voltage. Thus, the field at the needle tip is smaller than one would calculate for a metal from the tip radius and from the voltage in the vacuum between the end of the tip and the anode. This deficiency in field, which is superposed on that due to simple voltage loss in the needle, decreases when the needle resistance is reduced by illumination. The field emission accordingly increases. These considerations are attractive because they do not involve such large electric fields in the volume of the CdS as does a simple voltage drop in the spreading resistance.

Several of our observations were consistent with these general pictures. First, as mentioned above, illumination was correlated with changes in potential distribution around the emitting points. Second, when the light was switched off, the increase in applied voltage required to maintain constant current became larger

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[1] E. W. Mueller, Z. Physik **106**, 132 (1937).

[2] No phosphor coating was used here. The light produced would have returned to the CdS, of course, unless an opaque backing were used. Resultant feedback would have destroyed the significance of the results. A slight effect of this kind may even have been present without phosphor, since the transparent coated glass anode fluoresced faintly.

as the current level increased. Third, quenching phenomena were evident and were characteristic of CdS photoconduction.[3] Finally, atomic hydrogen destroyed the effects, presumably because the surface conductivity was increased by reduction of the CdS.

One expects other phenomena that are absent in metals to play a role in this kind of emission. Barrier layers are present. It is conceivable that a Zener type of breakdown may occur in a *p*-type semiconductor when emission is drawn from it. Further evaluation of these possibilities can perhaps best await theoretical treatment of field emission under these unusual conditions.

We are indebted to Malcolm H. Hebb and John K. Bragg for many interesting discussions

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[3] E. Taft and M. H. Hebb, J. Opt. Soc. Am. 42, 249 (1952).

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Nuclear Mass Determinations from Disintegration Energies: Oxygen to Sulfur

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Values of the atomic masses from O^{18} to S^{33} have been derived from the Q-values of nuclear reactions with a procedure of statistical adjustment. Tables are given of the most probable Q-values and the atomic masses. In combination with a previous calculation, they give a set of consistent mass values from n^1 to S^{33}, based on nuclear disintegration energies.

In a previous calculation[1] the atomic masses from n^1 to F^{20} relative to $O^{16}=16.000\,000$ have been derived from the Q-values of nuclear reactions. Following a similar procedure, the atomic masses from $A=17$ to 33 are derived in the present work from recently available Q-value measurements.

Table I lists the Q-values used in deriving the masses. In most of these measurements, electrostatic or magnetic analysis has been used to determine the energy of the incident particles and emitted particles: electrons, heavy particles, or pairs or converted electrons produced by gamma-rays. In some cases, reaction thresholds or radiative capture transition energies of thermal neutrons have been involved. Except in a few reactions, there is yet only one accurate measurement for each reaction. Fortunately, enough cross checks have been established to provide a test on the internal consistency of the data. In this calculation 46 reactions have been used to determine the masses of 29 nuclei. The extensive magnetic analysis work by W. W. Buechner's group at the Massachusetts Institute of Technology accounts for almost half of the reactions listed in Table I. Three connections between the heretofore very loosely linked Ne and F isotopes have been furnished by recent measurements: $F^{20}(\beta^-)Ne^{20}$, $Ne^{20}(d,\alpha)F^{18}$, and $Ne^{21}(d,\alpha)F^{19}$. The second one is a range measurement in photographic emulsion. However, in view of its accuracy and its consistency with other data, it has been included, in contrast to the practice in I. This is the only range measurement which is used in these calculations. Another difference from I is that measurements with reported errors up to 40 kev have been included, instead of the earlier limit of 30 kev. The error of the heavier of the resultant masses turns out to be of the order of 40 kev.

Figure 1 illustrates graphically the interconnections between the nuclei which are of interest in this discussion. The solid lines represent reactions forming nuclear cycles. As in I, these cycles are useful in that (1) they give values of certain fundamental mass differences (or zero); (2) these fundamental mass differences can serve as tests of internal consistency of the nuclear data; and (3) they can be used to make regional least-squares adjustment of the experimental Q-values and thereby to obtain the values of masses which are numerically consistent and, presumably, have some improved precision. The improvement in precision is a possible result of the adjustment of overdetermined but statistically consistent data.

Table II exhibits the simplest set of independent nuclear cycles in the region of interest in the present discussion. It can be seen that, while the general precision is somewhat inferior to that of reactions in I, the present data are statistically consistent and the values of fundamental mass differences computed from them are consistent with those derived from I, namely, $n-H^1=0.7823\pm0.001$ Mev, $n+H^1-H^2=2.225\pm0.002$ Mev, and $2H^2-He^4=23.834\pm0.007$ Mev. An exception is the fourth cycle in Group 4 of Table II. This cycle gives a value for $2H^2-He^4$ which is inconsistent with the other values for $2H^2-He^4$, the discrepancy being many times the average error of the other cycles. Therefore we have omitted this cycle in the adjustment of the Q-values. In order to calculate the masses of Ne^{22} and Ne^{23} we have adopted the (d,p) reaction Q-values without adjustment and have omitted the beta-

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[1] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951) (referred to as I).