TABLE I. Limits of isotopic abundance for hafnium and platinum.

Nuclide	Limit of abundance (%)
Hf^{170}, Hf^{171}	0.004
Hf^{172}, Hf^{173}	0.005
Hf^{175}	0.006
Pt^{188}, Pt^{189}	0.002
Pt^{191}	0.004
Pt^{193}	0.009
Pt^{197}	0.010
Pt^{199}	0.008
Pt^{200}	0.007

grant a Dempster-type double-focusing instrument was constructed,[1] but it soon became clear that this apparatus would need to be modified before it would be suitable for use in this work. However, in the process of ascertaining the limitations of the instrument, the two elements hafnium and platinum were examined with a view to setting limits of abundance for certain hypothetical stable isotopes. These limits are listed in Table I.

In this work the abundance of Hf^{174} was assumed[2] to be 0.18 percent and that[3] of Pt^{190}, 0.012 percent. The suggestion to examine hafnium[4] was made to us by M. L. Pool.

The senior author greatly appreciates the generous support of this work by the Research Corporation and regrets that events have so transpired that he has been prevented from continuing the project for which the grant was made.

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[4] We are indebted to Mr. E. B. Meservey for securing the hafnium wire used in these experiments.

Interactions of Remote Impurity Centers in Phosphors

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(Received January 14, 1952)

EVIDENCE is presented here which indicates that luminescence centers formed by manganese impurity atoms (ions) in rbhdl.—Zn_2SiO_4:Mn interact over several interatomic spacings. The interactions apparently can decrease the thermal activation energy for making nonradiative transitions from the excited state, without greatly affecting the energy difference (spectrum) of radiative transitions.

In the phosphor system symbolized by rbhdl.—Zn_2SiO_4:Mn, luminescence centers are produced by Mn activator atoms (ions) which occupy Zn sites substitutionally.[1] Variation of the proportion of manganese atoms N_{Mn} from about 0.001 to 10 percent of the number of Zn sites has a little effect on the spectrum of radiative transitions. This is evidenced by the relative invariance of the emission band peaked near 5250A.[2]

Variation of the Mn content, however, strongly influences the nonradiative transitions. This is indicated in Fig. 1 by concomitant changes in the decay time τ (at 25°C) of the nearly simple exponential decay of emission,[3] and the temperature breakpoint T_B (the operating temperature beyond which luminescence efficiency decreases rapidly).[4] These characteristics are related by

$$\tau=[a+\nu \exp(-\Delta E/kT)]^{-1},$$

where a is the temperature-independent constant for the radiative process, ν is a frequency factor, and ΔE is the thermal activation energy for making nonradiative transitions.[5] When $T=T_B$, the nonradiative Boltzmann term is appreciable relative to a.

As shown in the figure, luminescence efficiency $\mathcal{E}$ (at 25°C) also decreases rapidly beyond $N_{\mathrm{Mn}}\approx 1$.[6] (The maximum luminescence output from this system, with intense excitation, occurs for N_{Mn} somewhat greater than 1; i.e., when $\mathcal{E}$, T_B, and τ are all less than their maximum values.) The decline of $\mathcal{E}$ and maxima output can be correlated with the similar variation of τ and T_B by assuming that ΔE decreases with decreasing distance between centers. This behavior is readily described with a conventional energy *vs* configurational-coordinate ($\bar{x}$) diagram which shows the localized radiative transition occurring at small values of $\bar{x}$ and the nonradiative transition occurring at large values of $\bar{x}$.[7] The nonradiative transition, then, is more easily affected by a neighboring perturbation, such as another center.

Some insight into the constitutions of the luminescence centers may be obtained from a comparison of the foregoing curves with plots of the probability P of occurrence of isolated pairs of Mn atoms P_2, and isolated single Mn atoms PC_1 (assuming a random distribution of Mn's over Zn sites).[8] As may be seen in the figure, the curves P_2 and PC_1 do not decrease rapidly until $M_{\mathrm{Mn}}\gtrsim 10$; i.e., well above the region where T_B, τ, and $\mathcal{E}$ decrease rapidly. These comparisons indicate that (1) groups of two or more Mn atoms are not important as luminescence centers, in contradiction to hypotheses about clusters of activator atoms,[9] and (2) Mn atoms which have simply no nearest like neighbors (PC_1 at high values of N_{Mn}) may be operative as luminescence centers, but they probably have low values of ΔE which lead to small τ, T_B, and $\mathcal{E}$ as previously outlined.

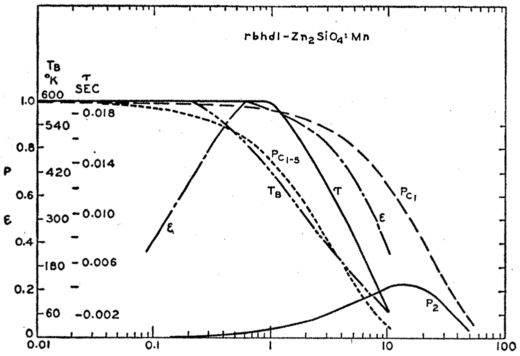

FIG. 1. Temperature breakpoint T_B of photoluminescence, decay time constant τ, and efficiency $\mathcal{E}$ of cathodo-luminescence, and probabilities of occurrence of (1) isolated pairs of Mn atoms P_2, (2) simple isolated Mn atoms PC_1, and (3) isolated Mn atoms without other Mn atoms in the 28 nearest available sites PC_{1-5}, as a function of the proportion of Mn in rbhdl.—Zn_2SiO_4:Mn.

A rough indication of the minimum remoteness for noninteracting centers was obtained by calculating and plotting the probability of occurrence of Mn atoms having no other Mn atoms anywhere in the five classes of nearest neighbors (C_{1-5}) comprising 28 Zn sites. A plot of this probability

$$PC_{1-5}=(1-0.01N_{\mathrm{Mn}})^{28}$$

is shown in the figure. The apparent coincidence of curve PC_{1-5} with curve T_B is probably not of quantitative significance, but the rapid decrease of PC_{1-5} in the same region as T_B and τ suggests that centers of this class represent roughly the degree of isolation required for efficient luminescence.

Such centers, without any other Mn atoms in the nearest 28 available sites, may still be only 12A apart, or less, even when the distance is calculated through intervening atoms. It seems reasonable to expect interaction over such small distances, and it is probable that appreciable interaction occurs over much larger distances, especially in ZnS-type phosphors where the optimum activator proportion is about 0.01 percent.

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[5] F. A. Kröger *et al.*, Physica **14**, 81, 425 (1948); see reference 6, p. 265.

[6] H. W. Leverenz, *An Introduction to Luminescence of Solids* (John Wiley and Sons, Inc., New York, 1950), Fig. 97, p. 330.

[7] Reference 6, Fig. 16b, p. 132.

[8] By *isolated* it is meant that there are no other Mn atoms in the six nearest Zn sites tround a pair of Mn atoms, and none in the four nearest sites around a single Mn atom (see reference 6, Fig. 142, p. 478).

[9] F. A. Kröger and P. Zalm, J. Electrochem. Soc. **98**, 177 (1951); see J. H. Schulman, J. Electrochem. Soc. **98**, 519 (1951).

The Stopping Power of a Metal for Charged Particles

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(Received January 15, 1952)

THE collective description of electron interactions[1,2] has been applied to the determination of the contribution of the conduction electrons in a metal to its stopping power for a fast nonrelativistic charged particle. This contribution is strongly influenced by the mutual interaction of the conduction electrons. The resulting polarization effect has been treated by Kramers,[3] who used a macroscopic description in which the electrons were treated as a continuum characterized by an effective dielectric constant, and by A. Bohr[4] who gave a microscopic description of certain aspects of the problem. With the aid of the collective description it is possible to obtain a somewhat more accurate expression for the stopping power of the metal, and, in addition, to obtain a more detailed understanding of the physical processes involved.

The conduction electrons are treated as a gas of point electrons embedded in a medium of uniform positive charge, and only the electron-electron interactions are here considered.[5] The interaction between the charged particle and the conduction electrons is analyzed by a classical calculation of the response of the density (or charge) fluctuations of this electron gas to the field of the charged particle. As shown in reference 2, these density fluctuations may be split into two components. One component is associated with organized longitudinal oscillations of the electron gas as a whole, the so-called "plasma" oscillations, which come about as a consequence of the electron-electron interactions. The frequency of these oscillations satisfies the following approximate dispersion relation:

$$\omega^2=\omega_p{}^2+k^2\langle V^2\rangle_{\mathrm{Av}}, \tag{1}$$

where $\omega_p{}^2=4\pi ne^2/m$, k is the wave number of the oscillations, and n, m, and $\langle V^2\rangle_{\mathrm{Av}}$ represent respectively the density, mass, and mean square velocity of the conduction electrons. This collective component describes in a natural way the effects of the long range of the electron interactions, and thus the polarization effects in the electron gas. However, due to the random kinetic motion of the individual electrons, the density fluctuations lose their collective behavior above a certain critical wave number k_0. Thus the density fluctuation also possesses an individual particles component, which is associated with the random kinetic motion of the electrons, shows no collective behavior, and may be treated independently of the collective component.

On this picture, the fast charged particle gives up energy to the conduction electrons in two distinct ways. Its long-range Coulomb interaction with the electrons, which may here be described by the collective part of the density fluctuations, results in the excitation of collective oscillations in the form of a wake trailing the particle. This phenomena resembles closely the Čerenkov radiation produced by fast electrons in a dielectric. The energy loss to the collective oscillations is obtained by calculating the reaction of this wake at the position of the particle. By a straightforward extension of the methods developed in reference 2, the energy loss per unit length to the collective oscillations is found to be

$$\left(\frac{dT}{dx}\right)^{(1)}=\frac{\pi nZ^2e^4}{E_0}\ln\left\{\frac{k_0{}^2[V_0{}^2-\langle V^2\rangle_{\mathrm{Av}}]}{\omega_p{}^2}\right\}, \tag{2}$$

where Ze represents the charge of the fast particle, E_0 its energy, and V_0 its speed,[6] which is taken to be $>V_F$, the speed of an electron at the top of the Fermi distribution. The response of the individual particles components of the density fluctuations to the field of the charged particle may be described in terms of short-range collisions between the particle and individual electrons. For the individual particles component represents a collection of individual electrons surrounded by co-moving clouds of charge which screen the electron fields within a distance of $\sim(1/k_0)$.[2] Thus the interaction between the charged particle and the individual electrons may be characterized by a screened Coulomb force of range $1/k_0$. The energy transfer in these short-range collisions may be calculated on the basis of the usual collision theory, and one obtains, for a classical calculation,

$$(dT/dx)^{(2)}=(2\pi nZ^2e^4/E_0)\ln(1.123/k_0b), \tag{3}$$

where b is the minimum impact parameter involved in the collision. (With a suitable choice of b, Eq. (3) also is correct for the appropriate quantum-mechanical calculation.[7])

The total energy loss to the conduction electrons is thus the sum of that expended in the excitation of collective oscillations and that lost in short-range collisions with the individual electrons. We obtain for the total energy loss per unit distance to the conduction electrons,

$$\frac{dT}{dx}=\frac{2\pi nZ^2e^4}{E_0}\ln\left\{\frac{1.123V_0}{\omega_pb}\left[1-\frac{\langle V^2\rangle_{\mathrm{Av}}}{V_0{}^2}\right]^{\frac{1}{2}}\right\}. \tag{4}$$

Our Eq. (4) differs from the results obtained by Kramers and A. Bohr in the factor $[1-\langle V^2\rangle_{\mathrm{Av}}/V_0{}^2]^{\frac{1}{2}}$ under the logarithm, which arose from our consideration of the dependence of the dispersion relation, Eq. (1) on the kinetic energy of the conduction electrons. This correction is comparatively small; e.g., for a 1-Mev alpha-particle incident on Be it leads to an increase in the effective average ionization potential of ~5 percent.

It is not expected that a quantum-mechanical description of the density fluctuations will alter the foregoing result appreciably, inasmuch as the dispersion relation is essentially unchanged, and though the cut-off wave number k_0 is somewhat changed from its classical value, this quantity cancels out in our final result.

[1] D. Bohm and D. Pines, Phys. Rev. **82**, 625 (1951).

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[3] H. A. Kramers, Physica **13**, 401 (1947).

[4] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys Medd. **24**, No. 19 (1948).

[5] The corrections due to the bending of the electrons in the lattice and the resistance of the metal are small (~5 percent) for Li and Be, the only metals for which the contribution of the conduction electrons to the stopping power is appreciable. See A. Bohr, reference 4.

[6] In obtaining Eq. (2), we have chosen as the maximum component of the collective oscillation wave vector perpendicular to V_0 a more accurate value than that used in reference 2, *viz.*, $\{k_0{}^2[1-(\langle V^2\rangle_{\mathrm{Av}}/V_0{}^2)]-\omega_p/V_0{}^2\}^{\frac{1}{2}}$.

[7] See N. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **18**, No. 8 (1948).

Capture Gamma-Rays from 277-Kev Protons on N^{14}

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(Received January 16, 1952)

THE γ-ray spectrum has been observed for the resonant capture of 277-kev protons by N^{14}. For such protons the only energetically permitted interactions with nitrogen are scattering or capture; thus, an observation of the spectrum yields rather definite information on the compound nucleus O^{15}. In addition a knowledge of the spectrum is useful since nitrogen is often a target contaminant.