distances, especially in ZnS-type phosphors where the optimum activator proportion is about 0.01 percent.

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The Stopping Power of a Metal for Charged Particles

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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 non-relativistic 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

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

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,

$$(dT/dx)^{(2)} = (2\pi n Z^2 e^4/E_0) \ln(1.123/k_0 b), \tag{3}$$

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,

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

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 $\sim$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.

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[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.*, $\{k_0^2[1 - (\langle V^2 \rangle_{\mathrm{Av}}/V_0^2)] - \omega_p/V_0^2\}^{\frac{1}{2}}$.
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Capture Gamma-Rays from 277-Kev Protons on N^{14}

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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.

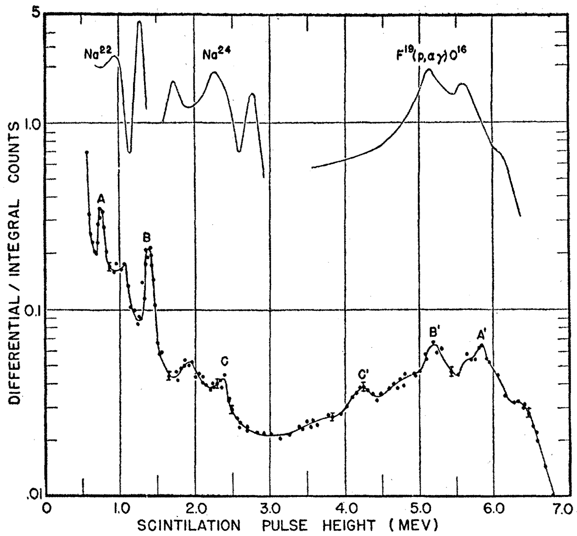

FIG. 1. Scintillation pulse-height spectrum (lower curve) for γ-rays produced by 277-kev protons on N^{14}. The ratio of differential to integral counts is plotted as a function of pulse height in Mev. Standard deviations of all data points are five percent and are indicated for scattering points on the curve. In the upper part of the figure is shown the pulse-height distributions for γ-rays from Na^{22} and Na^{24} and γ-rays from 340-kev protons on F^{19}.

An analyzed proton beam of from 200 to 400 μa from the Cockcroft-Walton generator impinged on a thick TaN target which had been formed by inductively heating a tantalum disk in a nitrogen atmosphere. Gamma-rays were detected by a NaI(Tl) crystal 2 inches long and 1.5 inches in diameter placed at 0° with respect to the proton beam. Scintillations were detected and analyzed by a 5819 photomultiplier, linear amplifier, and a single-channel analyzer.

A thick target yield curve showed a rise near 277 kev in agreement with the $N^{14}(p, \gamma)O^{15}$ resonance observed by Tangen.[1] The proton energy was set about 10 kev above the resonance and the pulse-height distribution in the lower part of Fig. 1 was obtained. Energy calibrations were made using γ-rays from Cs^{137} (0.661 Mev),[2] Na^{22} (1.277 Mev),[3] Na^{24} (2.755 Mev),[4] and the 6.13 Mev[5] γ-ray from 340-kev protons on F^{19}. To aid in the interpretation of the nitrogen spectrum the pulse-height distributions of the various calibration γ-rays is shown in the upper part of Fig. 1. Radiations from Na^{22} and Na^{24} produce photoelectric peaks at the γ-ray energies accompanied by Compton peaks at slightly lower energies. Na^{24} also exhibits a pair group 1.02 Mev below the γ-ray energy. A comparison with the nitroben spectrum indicates that groups B and C of Fig. 1 are photoelectric peaks accompanied in each case by a Compton group of slightly lower energy. Pairs associated with C contribute very little to the peak at B. Peak A is also a photoelectric peak whose Compton group is buried in the background.

In the higher energy region pair production predominates to give a pulse-height distribution which is illustrated by the $F^{19}(p, \alpha\gamma)O^{16}$ spectrum shown in the upper part of Fig. 1. The single γ-ray produces a triple peak by the following process. A part (1.02 Mev) of the γ-ray energy is used for pair production and reappears as annihilation radiation at the end of the positron track. Since the annihilation radiation usually escapes the crystal, the most prominent group of pulses is 1.02 Mev below the γ-ray energy. Occasionally one or both 0.51-Mev annihilation radiations are captured in the crystal so that the observed distribution shows subsidiary peaks 0.51 Mev and 1.02 Mev above the main group.

A comparison of the nitrogen and fluorine distributions indicates that groups A', B', and C' are pair peaks each 1.02 Mev below their γ-ray energies. A subsidiary peak associated with A' is clearly resolved, and there is some indication of subsidiary peaks above B' and C'. Thus the pulse-height distribution of Fig. 1 results from six γ-rays designated as A, B, C, C', B', A', whose energies are 0.75±0.03, 1.39±0.03, 2.38±0.10, 5.29±0.10, 6.21±0.10, and 6.84±0.10 Mev, respectively.

Gamma-rays from protons on nitrogen can arise only from capture followed by positron decay to N^{15}. Positron decay could leave N^{15} with up to 1.68-Mev excitation; however, since the observed positron spectrum is apparently not complex[6] and since no low-lying states are known in N^{15},[7] it is assumed the decay occurs to the ground state and all γ-rays result from direct capture. According to recent mass values,[8] 277-kev protons on N^{14} form O^{15} with 7.60-Mev excitation energy. The six γ-rays contributing to the distribution of Fig. 1 can be attributed to proton capture by nitrogen only if there are three intermediate levels in O^{15} giving rise to three cascade processes of two γ-rays each. These cascade groups are AA', BB', and CC', and their energies add to the total excitation as follows:

$$A+A'=0.75+6.84=7.59\pm0.13 \text{ Mev}$$
$$B+B'=1.39+6.21=7.60\pm0.13 \text{ Mev}$$
$$C+C'=2.38+5.29=7.67\pm0.20 \text{ Mev.}$$

The strongest groups B and B' must certainly be assigned to nitrogen since the integral yield curve shows the 277-kev resonance. The weaker groups (A, A', C, and C') could possibly be attributed to target contaminants; however, the fact that they can be arranged in cascade groups in the above manner is strong evidence that all observed γ-rays come from nitrogen. No direct transition to the ground state was found.

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Extremely High Energy Nuclear Interactions*

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BY utilizing the technique of an "emulsion cloud chamber" to select high energy events[1] we have studied the angular distribution, multiplicity of penetrating particles, and ratio of

TABLE I. Summary of data.

(1) Shower and primary	(2) Number of charged particles (N_{ch})	(3) $\frac{N_{\pi^0}}{N_{ch}}$[a]	(4) $\gamma\times10^{-3}$	(5) X	(6) $\frac{r}{R}$	(7) N_{ch} (Fermi)[b]
$A(\alpha)$	21(84)	0.6±0.2	3	1.17	0.18	15
$178(\alpha)$	23(92)	0.72±0.15	6	2	0.46	14
$R(\alpha)$[c]	14(56)	0.75±0.25	0.48	2.33	0.57	6.6
$77(p)$	24	···	4	1.17	0.18	16.5
$104(p)$	20	0.5±0.3	1.3	1.33	0.23	11.7
$67(p, n)$	9	1.2±0.5	4.5	1.33	0.23	16
$60(p, n)$	26	···	19.5	1.33	0.23	23
$91(p, n)$	16	0.6±0.35	1.3	1.7	0.34	10.8
$17(p)$	24	1.1±0.3	5.1	3.7	0.76	7.9
$59(p)$	24	0.5±0.3	8.9	4	0.78	8.8
$66(p, n)$	11	0.75±0.4	0.64	6.67	0.87	2.7
$T(p)$	36	0.6±0.2	19.4	6.67	0.87	6.3
$Z(p, n)$	15	0.5±0.25	50	24	~1	≤3.4
$S(p)$[d]	15	···	32	···	~1	≤6
$G-L(p)$[e]	18	···	23	≥9	~1	≤6
		Av. 0.71±0.3				

[a] This ratio is not corrected for seconday nuclear interactions. An approximate estimate for this indicates that the observed ratio can be lowered by as much as 30 percent. The correction will vary for each individual shower.
[b] See reference 4.
[c] Kaplon, Peters, and Bradt, Phys. Rev. **76**, 1735 (1949).
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[e] See reference 7.