

For wire collection a greater partial pressure will be required.

It is possible to analyze the boron content of these films by quantitative chemical techniques and films of this type have been used to calibrate the National Bureau of Standards thermal-neutron flux to an error of less than 2 percent.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to Dr. L. F. Curtiss for his interest and advice, to L. Costrell for assisting with the electronics problems, to A. Krinsky for preparing the boron films, and to D. Padgett for taking some of the measurements.

Influence of Chemical State on Stopping of Fast Charged Particles*†

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(Received October 13, 1953)

The suggestion is made to use the characteristic electron dispersion frequencies or corresponding wavelengths (λ_0) from molar refraction data for the prediction of influences of the chemical state on the stopping power of fast charged particles. Changes in λ_0 for atoms in different chemical states are transformed into changes in mean excitation potentials in the Bethe-Bloch theory and to changes in stopping power. Mass absorption data for Bi²¹⁰ beta rays by Fournier are corrected for the anomalous Z/A -factor for hydrogen and then show the predicted effects for different groups of hydrocarbons. The very accurate data by T. J. Thompson on fast protons are compared with those from the " λ_0 approach" for a number of cases. Qualitative agreement is present for most of them but quantitatively the situation is less satisfactory. Certain favorable cases of large anomalies, not yet investigated, are predicted.

THE influence of the chemical state on the stopping power of fast charged particles was suggested by Bothe¹ to be caused by changes in the dispersion frequencies present in the Bohr stopping theory.² A more detailed and modern discussion³ involves the oscillator strengths at different frequencies and its influence on the mean excitation potential in the Bethe-Bloch theory.

The problem of estimating changes in excitation potentials, without waiting for detailed information on the complete valence electron absorption spectrum of light, might be approached by evaluating the dispersion frequencies from *refractive index data*. This was done by Bohr² for H₂ and He, but the procedure should be generalized to polyatomic substances in any state of aggregation (except conductors). The characteristic frequency, ν_0 (or wavelength λ_0), is obtained for a variety of substances from molar refraction

$$R = \frac{n^2 - 1}{n^2 + 2} \frac{M}{d} = \text{const} \frac{1}{\nu_0^2 - \nu^2} \quad (1)$$

The value of λ_0 is a sort of mean value, the oscillator strengths of the various transition possibilities being

taken into account.⁴ As about the same excitation phenomena occur with light and with charged particles,⁵ one should be allowed to attribute changes in λ_0 to corresponding changes in stopping power. The use of the ionization potentials may sometimes be of value but would not be general enough for our purpose.

Evaluation of λ_0 for the lightest elements in different chemical states by means of atomic⁶ and molar refraction data gives a picture rather analogous to that of chemical refractometry; i.e., those compounds which show increments in refraction (due to absorption in the near ultraviolet⁶) also show increments in stopping power compared with some standard. Aromatic hydrocarbons are, for instance, expected to show higher stopping power than aliphatic ones.

In a study of the mass absorption coefficients of Bi²¹⁰ beta rays for 17 hydrocarbons, Fournier⁷ reported large increments (as much as 12 percent) but apparently neglected the anomalous Z/A -factor for hydrogen. After appropriate corrections, by use of a reasonable figure for the hydrogen mass absorption coefficient, the values for the increments are reduced to 3 percent or less. Grouping the data belonging to different hydrocarbon classes together, we find interesting differences as shown in Fig. 1. Actually the same sequence is expected from the λ_0 -approach, although the experi-

* Read before the Thirteenth International Congress of Pure and Applied Chemistry, Stockholm, Aug. 1, 1953.

† This work was supported by the Swedish Atomic Committee.

¹ W. Bothe, *Jahrb. Radioakt. u. Elektronik* **20**, 46 (1923); *Handbuch der Physik* (J. Springer, Berlin, 1933), Vol. 22, No. 2.

² N. Bohr, *Phil. Mag.* **25**, 10 (1913); **30**, 581 (1915).

³ R. Platzman, *Symposium on Radiobiology*, Oberlin College, edited by J. Nickson (John Wiley and Sons, Inc., New York, 1952), Chap. 9.

⁴ K. L. Wolf and K. F. Herzfeld, *Handbuch der Physik* (J. Springer, Berlin, 1928), Vol. 20.

⁵ H. A. Bethe, *Ann. Physik* **5**, 325 (1930).

⁶ N. A. Sørensen, *Ann. Chem. Justus Liebig's* **546**, 57 (1941).

⁷ G. Fournier, *Compt. rend.* **196**, 412 (1933); *Actualités sci. et ind.* **57**, (1933).

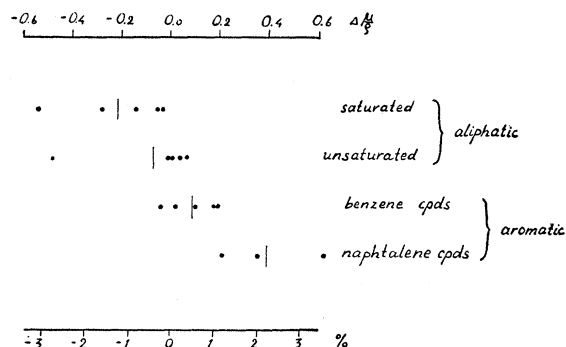


FIG. 1. Deviations in mass absorption coefficient (cm^2/g) for different classes of hydrocarbons according to revised Fournier data (reference 7) for Bi^{210} beta rays. The circles represent values for various hydrocarbons belonging to the groups indicated. The mean of the values in each row is indicated by a vertical line. Note the shifts of these lines for different chemical structures.

mental increments are apparently larger. This might be caused by the uncertainty in the assumed mass absorption coefficient for hydrogen. Range studies of P^{32} beta rays in this laboratory (unpublished) also show aromatic hydrocarbons to have a larger stopping power than aliphatic ones.

It is of interest to compare these results with the stopping data for 340-Mev protons and the corresponding excitation potentials evaluated by Thompson,⁸ whose work is probably the most accurate in this field. Table I shows the changes in mean excitation potential expected from the λ_0 approximation and reasonable assumptions on the number of valence electrons, as well as the corresponding experimental changes determined by Thompson. Qualitative agreement is present in all accessible cases of comparison according to Table I. The quantitative picture is bad, the probable reasons being difficulties in accurate evaluation of atomic refractions and the exact number of valence electrons and the fact that (1) may not reflect the changes correctly because of its mathematical form.

⁸ T. J. Thompson, University of California Radiation Laboratory Report UCRL-1910, 1952 (unpublished).

Even if the λ_0 approach is an approximation, it should be regarded as a rough guide to chemical effects in stopping power. It shows that the most extreme cases have perhaps not yet been studied experimentally, e.g., compounds absorbing strongly in the near ultraviolet region such as anthracene and other polyaromatic substances as well as substances having strong electronic absorption bands in the visible region, e.g., many colored substances. These interesting possibilities are part of a research program with monoenergetic betatron electrons in this laboratory. Moreover, the theoretical

TABLE I. Chemical effects in energy loss of fast charged particles. Summary of experimentally established changes in mean excitation potentials^a (ΔI) and changes estimated by means of optical dispersion data. All values are expressed in ev. C_{e1} means elementary carbon (graphite). H_2 , O_2 , and N_2 refer to the liquid state.

Element	Case compared	Dispersion theory, ΔI	Thompson experiments, ΔI	Qualitative agreement
Hydrogen $Z=1$	$\text{H}_2 - \text{H}_{\text{aliphatic}}$	+0.7	+2.7	+
	$\text{H}_2 - \text{H}_{\text{arom}(\text{benzene})}$	+4.8	+5.2	+
	$\text{H}_2 - \text{H}_{\text{arom}(\text{naphthalene})}$	+5.9	— ^b	+
Carbon $Z=6$	$C_{e1} - C_{\text{aliph}}$	+4.8	+0.9	+
	$C_{e1} - C_{\text{arom}}$	+10.1	+3.0	+
	$C_{e1} - C_{\text{CCl}_4}$	+6.2	+12	+
Nitrogen $Z=7$	$\text{N}_2 - \text{N}_{\text{nitrobenzene, aniline}}$?	-13	?
	$\text{N}_2 - \text{N}_{\text{pyridine}}$?	+7.5	?
Oxygen $Z=8$	$\text{O}_2 - \text{O}_{\text{ether}}$	-4.7	-0.2	+?
	$\text{O}_2 - \text{O}_{\text{acetone}}$	+6.1	+8.5	+
	$\text{O}_2 - \text{O}_{\text{OH}}$	-4.9	-0.2	+?

^a See reference 8.

^b Fast electrons (reference 7); excitation potential change not known.

difficulties in this field stress the need for more experimental data.

A more detailed account will be given elsewhere.

The author wishes to thank Professor O. Lamm for the initiation and valuable support of this study and his never-failing interest throughout the work.