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J. Neufeld

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ON THE RELATIONSHIP BETWEEN THE CHARGE OF AN ION AND ITS VELOCITY

Jacob Neufeld

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ON THE RELATIONSHIP BETWEEN THE CHARGE OF AN ION AND ITS VELOCITY

Jacob Neufeld

I. INTRODUCTION

A. General

A heavy particle passing through matter undergoes very complicated processes of electron capture and loss as a result of which the charge of the particle continually fluctuates. The problem of determining the average charge of the particle has received considerable attention as a result of the pioneer investigations of Bohr (Bo 40) and Lamb (La 40) that followed the discovery of fission. Within recent years, due to the rapidly increasing technological progress in the atomic energy field, this problem has become of importance in a great variety of fields such as in the study of damage in various substances due to fast fission products and other heavy particles, in biological studies, in the determination of absorbed dose in various investigations dealing with the fission process, etc. There is also a considerable interest in the development of efficient techniques for producing very highly stripped ions and recent investigations relating to the effect of the medium on the charge of a moving ion would be of primary importance in that connection. There are now two projects in the United States dealing with accelerators specifically designed to accelerate highly stripped ions. One of these is located at the Radiation Laboratory of the University of California and the other at Yale University.

At the present time there appears to be no rigorous and usable theory that would serve to predict the charge of a known ionic species of

known energy and moving in a known medium. A quantum mechanical approach has been successfully used in simple cases dealing with hydrogen atoms moving through a gas consisting of atomic hydrogen and within recent years a number of papers has appeared on this subject (Ba 52; Ba 53; Ba 53a; Ba 55; Da 53; Ja 53). However, there is little likelihood that this approach will lead, at least in the immediate future, to successful practical results that would be applicable to heavier ions, such as fission fragments. Other methods have been used that are mainly based on statistical considerations and in many instances the results obtained are not in a satisfactory agreement with the experiment. Therefore, empirical factors have been applied in order to "patch up" the discrepancies between the theory and experiment.

In the present investigation we shall consider methods based on the Bohr-Lamb theory, on the Dmitriev theory, and methods involving studies of charge exchange collisions. These methods will be correlated with experiments in order to determine insofar as it is possible the accuracy of the proposed theories.

B. Bohr-Lamb Theory

This theory formulated independently by Bohr (Bo 40) and by Lamb (La 40) is based on an assumption that a "heavy" ion (i.e., an ion having a large nuclear charge Z) when passing through a medium is stripped of all its orbital electrons that have velocities smaller than the translational velocity of the ion. This assumption is based on essentially qualitative considerations. Thus Bohr argued that when a moving ion collides with the atoms of the surrounding medium the less

firmly bound electrons are more easily removed, and when capture takes place it is more likely to occur in orbits associated with velocities of the same order of magnitude as the translational velocity of the ion. Somewhat different considerations have been presented by Lamb who argued that the moving ion is stripped down of its outermost electrons until the ionization potential of the next stage of ionization is greater than the kinetic energy of electrons bombarding the ion with velocity V where V is the translational velocity of the ion.

Since the Bohr-Lamb theory is not supported by rigorous arguments it would be desirable to ascertain as to whether it is in agreement with experimental data and if such an agreement exists, what is its margin of accuracy. Such work was undertaken soon after the formulation of this criterion, however, due to the paucity of experiments to date, it is difficult to give a relatively complete evaluation of the merits of the criterion.

It appears from published literature that two models of ions have been used in order to correlate the experimental data with the electronic orbital velocities, i.e., the Bohr model (Bo 48) and the Knipp and Teller model (Kn 41). Both models are statistical and give values of relatively low order of accuracy. Some experimenters correlated their measurements with these statistical models claiming a correlation of a higher order of accuracy than the one inherent in the model. It is somewhat surprising to see that the more refined calculations of electron binding energies in various ions have been apparently completely ignored. This applied particularly to the values given by Lisitzin (Li 38) which have been

known since 1938 and published in 1943 in a general reference manual (Da 43). Some of the estimates made by Lisitzin have been further refined by Finkelnburg (Fi 47; Fi 55). A complete table of the ionization potentials of all the electronic orbits in various ions has been computed by Harris Mayer in collaboration with the Los Alamos computing group. These calculations are based on a Los Alamos report of Mayer (Ma 47).

C. Dmitriev Theory

The theory formulated by Dmitriev (Dm 57) is based on the following assumptions:

(1) Consider a monoenergetic beam of N atoms passing through a medium with velocity V and losing some of its orbital electrons as a result of the interaction with the medium. Let N_i designate the number of those atoms that have lost an electron belonging to the ith orbit. The value $N_i/N = P_i$ is represented as

$$P_i = P(V/v_i) \tag{1}$$

i.e., it is assumed that there is a unique dependence of the value P_i on the ratio between the translational velocity V of the ion and the orbital velocity v_i of the escaped electron. This dependence is applicable to any atom including hydrogen, and therefore the expression (1) corresponds to the ratio of $H^+/(H^o + H^+)$ and represents the fraction of hydrogen beam that is positively charged as a result of its interaction with the surrounding medium. The function (1) has been determined by Dmitriev

from the measurements on hydrogen beams made by Bartels (Ba 32), Kanner (Ka 51), and Stier, Barnett and Evans (St 54).

It should be noted that the event represented by the function P_i is likely to occur if i represents the external electronic orbit. On the other hand the situation in which an internal electronic orbit of the order i is removed from the atom while all the external orbits remain undisturbed is not likely to occur.

(2) The events represented by P_i for various values of i are assumed to be independent of each other and accordingly, the average charge of an ion has been represented as

$$Z^*_{av} = \sum P_i \tag{2}$$

The above assumptions are somewhat controversial and a physical justification would be desirable. The values v_i in the expression (1) have not been explicitly defined, i.e., it has not been stated whether v_i represent orbital velocity in a neutral atom or in a partly ionized atom. However, it appears from the assumptions made by Dmitriev that v_i should refer to a neutral atom.

II. CORRELATION OF THE BORH-LAMB THEORY WITH EXPERIMENT

A. Model of an Ion

In order to ascertain the validity of the Bohr-Lamb theory, one needs to correlate the measurements of the ionic charges with a model of an ion in which the orbital velocity of the most external electron is known as a function of its binding charge. A model has been suggested by Bohr (Bo 48) which is a simplification of the Thomas-Fermi atom. Assuming that n = 1 represents the outermost electron and n = 2, 3, 4 represent electrons having correspondingly increasing binding energies, this model yields for the orbital velocity v_n of the nth electron the following value,

$$v_n = \frac{n}{\nu} \quad \text{atomic units} \tag{3}$$

where ν is the "effective quantum number." (The expression (3) and all subsequent formulas shall be expressed in atomic units (Ha 28)). For an outermost electron in a neutral atom $\nu \sim 1$. For inner electrons ν increases with n and reaches a value approximately equal to $Z^{1/3}$ for n somewhat smaller than Z/2 where Z is the atomic number. When n is increased further, ν decreases in value and reaches $\nu \sim 1$ for the most firmly bound electron. These estimates are very approximate and presumably can be applied to a neutral atom as well as to an ion in which a large portion of orbital electrons has been stripped off. This model has been subsequently modified by Lindhard and Scharff (Li 53) who used

instead of $v \sim Z^{1/3}$ the value $v \sim K\, Z^{1/3}$ where $K < 1$.

According to Bohr the value $v \sim Z^{1/3}$ corresponding to intermediate values of n shows a flat maximum that is applicable to a relatively large number of orbital electrons and, therefore, he assumed that a charge of a fission fragment can be roughly represented as

$$Z^*_{av} \sim Z^{1/3}\, V \tag{4}$$

The expression (4) agrees well with the experimental values for a heavy fission fragment ($Z = 54$) having $V = 4$ since it gives $Z^* = 15$. However, for a light fission fragment ($Z = 38$) having $V = 6$ we obtain from (4) $Z^* = 20$ while the measured value is about 16. According to Bohr and Lindhard (Bo 54), the agreement for a heavy fission fragment is due to the fact that Z^* is somewhat smaller than $Z/2$ and therefore the value $v \sim Z^{1/3}$ is applicable whereas for a light fission fragment the value Z^* is not "somewhat smaller" than $Z/2$ and, therefore, a discrepancy occurs. Unfortunately the Bohr model is not defined more specifically for cases in which v differs from $Z^{1/3}$ and therefore the practical applicability of this model is very limited.

A more detailed study of the statistical model of the Thomas-Fermi ion has been made by Knipp and Teller (Kn 41) and Brunings, Knipp and Teller (Br 41). These authors have plotted a series of graphs representing for each ion a functional dependence between the velocity of the most loosely bound electron v_{TF} and the corresponding binding charge Z^*_{TF}.

The most loosely bound electron has been defined in case (a) as the outermost electron and in case (b) as the electron having the lowest binding energy. The authors have introduced an empirical parameter γ such that

$$\gamma = \frac{v_{TF}}{V} \tag{5}$$

where v_{TF} is the velocity of the most loosely bound electron having a binding charge $Z^*_{TF} = Z^*_{av}$. Under the assumption (a), γ was found to decrease with atomic number ($\gamma = 0.6$ for $Z = 6$ to $\gamma = 0.35$ for $Z = 55$) and under the assumption (b) γ was found to increase with atomic number ($\gamma = 1.3$ for $Z = 6$ to $\gamma = 1.8$ for $Z = 55$). It should be kept in mind that no accurate measurements of ion charges were available at the time this investigation was made. For determining charges other than those of fission fragments the authors relied on range energy measurements in various gas mixtures and in order to determine the ion charges they used an approximate relationship,

$$\sigma_e = \langle i^2 \rangle_{av} \, \sigma'_e \tag{6}$$

where σ_e is the "electronic" component of the stopping power, $\langle i^2 \rangle_{av}$ is the mean square charge of the ion and σ'_e is the "specific electronic cross section". Some of the errors resulting from the above formula are due to the neglect of the influence of the medium and also to the fact that the contribution of the stopping power due to electron capture and loss processes has been neglected.

One of the fundamental merits of the treatment by Brunings, Knipp, and Teller is its potential usefulness for immediate practical purposes since by introducing a semi-empirical parameter such as γ the accuracy of the estimates involving the Bohr-Lamb criterion may be considerably improved. However, the parameter γ would be of value only if a sufficient number of experiments would establish its adaptability for practical purposes. It would also be desirable to correlate the experimental data not with a statistical ion but with a more refined model based on the calculations of Lisitzin, Mayer and Finkelnburg since these calculations take into account the individual behavior of each orbital electron.

The calculations of Lisitzin are based on empirical rules concerning a sequence of isoelectronic systems, i.e., systems having the same number of electrons and obtained by removing one, two, three ... electrons from the first, second, and third ... succeeding elements in the periodic table (such as, for instance, Na, Mg^{+}, Al^{++}, Si^{+++}, P^{++++}, etc.). The regularity of the ionization potentials in an isoelectronic sequence has been studied by many investigators in the past and a review of this subject together with a compilation of a great many experimental data is contained in Lisitzin's paper. Some of the estimates of Lisitzin have been further refined by Finkelnburg on the basis of different semi-empirical considerations.

The calculations made by Mayer utilize shielding constants similar to those of Slater (Sl 30). The ionization potential is then of the form

$$I = \frac{(Z - S)^2}{2n^2} \tag{7}$$

where n is the principal quantum number of the outermost electron and the term S is due to the shielding by the other electrons in the ion. The shielding terms are obtained by means of hydrogenic wave functions as shown in Mayer's report which gives a table of their values.

The results of Mayer are not accurate for nearly neutral ions but they give very acceptable results for highly ionized ions. It is noted that semi-empirical considerations of Lisitzin and Finkelnburg and theoretical considerations of Mayer lead to independent results that are in a quite good agreement one with another and also in good agreement with the experimental data.

B. Measurements

From the survey of literature it appears that many experiments were made on ions of hydrogen and helium and relatively few experiments dealt with heavier ions. The only ion species on which some experimental data are published are Li, N, O, F, Ne, Sr, and Xe. These data are plotted in Figs. 1 through 7 in which Z^*_{av} represents the charge of an ion and V the corresponding velocity.

The data relating to Sr, and Xe are meant to correspond to light and heavy fission fragments, respectively. Each of these fragments has a continuous spread in atomic number and both Sr and Xe are considered as "the most representative" species. The data relating to lighter ions are definitely associated with a specific ionic species. The measurements on fission fragments made originally by Lassen (La 51 and La 51a) are indicated in Figs. 6 and 7 with full circles and the corresponding data

recently obtained by Fulmer and Cohen (Fu 57) are indicated with open circles. These two sets of measurements differ mainly in the determination of the velocity of fission. Thus, as indicated by Leachman and Schmitt (Le 54), the initial velocity of heavy and light fission fragments are $v = 4.42$ and $v = 6.48$ whereas the values given by Lassen are $v = 4$ and $v = 6$, respectively. If we take into account the discrepancy in the velocity determination, we obtain a quite satisfactory agreement between the measurements of Lassen and Fulmer and Cohen in such media as hydrogen and helium (difference is less than 2%). However, there is a discrepancy in the measurement in argon. Thus, for $v = 6.6$ for light fragments the value reported by Lassen is $Z_{av} = 15.4$. Using the correspondence between the above sets of measurements we assume that the velocity of heavy and light fission fragments $v = 3$ and $v = 5$ as obtained by Lassen correspond to velocities $v = 3.3$ and $v = 5.5$ in the measurements of Fulmer and Cohen.

In order to correlate the above experimental data with values that could be obtained by means of the Bohr-Lamb theory, we have plotted in Figs. 1 through 7 curves representing the relationship between the outermost orbital velocity v of an ion and the corresponding binding charge Z^*. The curves designated as L, M, and F are based, respectively, on the estimates of Lisitzin, Mayer, and Finkelnburg. The electron velocities are calculated assuming that each electron is in a central Coulomb field characterized by the corresponding binding charge. These curves represent an interpolation of the data of Lisitzin, Mayer, and Finkelnburg in which the discrete points representing the binding energies

and velocities of neighboring orbits have been connected by straight line segments. Thus each of these curves represents the relationship between the velocity of the ion and the corresponding charge when the following two assumptions are satisfied: (a) a stripping of the outermost orbit occurs only when the velocity V of the ion exceeds by a very small amount the velocity v_n of the orbital electron and as a result of the stripping the charge of the ion is equal to the binding charge corresponding to the orbital electron of velocity v_n; (b) the charge of the ion Z^* is a linear function of its velocity v over a short range bounded by the velocities of two neighboring electron orbits.

It is apparent from Figs. 1 - 7 that the Bohr-Lindhard theory can give, at best, a rough estimate of the average charge of the moving ion and, therefore, in order to obtain more refined values, we have to consider the applicability of an empirical parameter. Furthermore, it is seen that the average charge is not a unique function of the velocity, and therefore, we have to provide such an empirical parameter that would take into account the nature of the stopping medium. We shall consider the dependence between the charge of a moving ion and the following parameters: the species of the stopping atom, the pressure of the medium if the particle passes through a gas, and the effect of the state of condensation of the medium.

(1) The species of the stopping atom

<u>(a) Gaseous medium.</u> According to Lassen, Z^*_{av} of a "heavy ion" in a gaseous medium depends very significantly on the species of the stopping atom. Thus a heavy fission fragment at V = 4 has Z^*_{av} about

25.8% higher in argon than in helium. Hubbard and Lauer (Hu 55) performed measurements similar to those made by Lassen on neon ions having velocity V = 3.77 in hydrogen, helium, and nitrogen, and on oxygen ions having velocity V = 4.25 in nitrogen, krypton, and xenon and reported no significant dependence between the average charge of the ion and the nature of the medium. However, they did not preclude the possibility of differences in magnitude of the order of 10%.

(b) Solid or liquid medium. It is of interest to note that the dependence between Z^*_{av} and the character of the stopping atom is somewhat less pronounced in a condensed medium than in a gas. According to Lassen the variation in values of Z^*_{av} for fission fragments passing through various solids is less than 10%. A similar dependence can also be seen by comparing the measurements of Z^*_{av} measured by Reynolds, Scott, and Zucker (Re 54) in nickel (Z = 28) with the corresponding values measured by Reynolds, Wyly, and Zucker (Re 55) in Formvar ($Z \sim 4$) and a comparison of these two measurements shows rather unexpectedly that Z^*_{av} is higher in a stopping medium having a lower atomic number. A similar result has been obtained by Lassen who found that the charge of a fission fragment decreases if the atomic number of the stopping medium is higher.

(2) The pressure of the gaseous medium

According to Lassen (La 51a) the average charge of a fission fragment increases with the pressure. Thus the Z^*_{av} for a fission fragment in argon at a pressure of a few mm of Hg is about 16. This charge increases relatively fast with the pressure until it reaches a limiting value of 19 at a pressure of about 70 mm of Hg. For pressures exceeding

this value, it increases very slowly. This dependence between the pressure of the gas and the charge of the ion has not been observed by Hubbard and Lauer in their experiments on ions of oxygen and neon. This is apparently due to the fact that the highest pressure that they used was about 0.1 mm of Hg and at this pressure the effect was not detectable.

The pressure effect, according to Lassen, depends upon the relative values of two time intervals designated as T_{coll} and T_{exc}. The value T_{coll} represents the average time interval separating two successive charge exchange collisions between the moving ion and the stopping atoms, and the value T_{exc} is the radiative life time of the ion in an excited state. It is apparent that after a collision one or more orbital electrons carried by the ion are often left in an excited state. If the pressure is relatively high, we have $T_{exc} > T_{coll}$ and there is a high probability that an electron in an excited state will be removed from the ion in the next collision. The higher the pressure, the more frequent are the collisions in which the excited electron is removed from the ion and the more efficient is the process of stripping the external orbital electrons from the ion. On the other hand, for lower pressures we have $T_{exc} < T_{coll}$ and an electron that is initially excited as a result of a collision has time to return to the ground state before the next collision takes place. At the next collision the probability of knocking out the electron from the ground state is smaller than if the electrons were excited, and therefore, the process

of stripping the ion from its orbital electrons is less efficient at a lower pressure.

Therefore, in order to have an appropriate ionic model which would take into account the pressure effect, one has to consider the distribution of electronic orbital velocities in an ion that is continually perturbed by collisions with the atoms of the stopping medium. Such models have not been submitted to date and both statistical models given by Bohr and by Brunings, Knipp, and Teller relate to an ion in the ground state.

The experimental data for Z^*_{av} in gases plotted in Figs. 1 - 7 relate to measurements at very low pressures at which the pressure effect is not significant. In particular, the values for fission fragments are extrapolated to zero pressure. Thus a heavy fission fragment emitted from uranium into a vacuum ($p \sim 10^{-3}$ mm) in the deflection chamber has an average charge 21.6 resulting from the equilibrium attained within the mass of uranium. This charge decreases if the deflection chamber is filled with argon and as the pressure is increased. This charge reaches a minimum value of about 15 when the pressure $p \sim 0.5$ mm of Hg. Then when the pressure increases further, the charge increases linearly at a relatively small rate. Lassen has extrapolated the linear part of this relationship to the value $p = 0$ and thus defined the equilibrium charge for zero pressure.

(3) The state of condensation of the medium

It has been observed that an ion passing through a solid or

liquid has a higher charge than an ion of the same velocity passing through a gas. This effect may be considerable, particularly in case of heavy ions. Thus, according to Lassen (La 51a), a fission fragment passing through helium at velocity V = 3 has an average charge 8.6 but the same ion emerging with the same velocity from a layer of mica has a charge 109% higher. Unfortunately the experimental evidence regarding the state of condensation effect for lighter ions is not very conclusive. According to Hubbard and Lauer (Hu 55) an oxygen ion at E = 6.1 Mev has a charge $Z^*_{av} = 4.8$ in a gas and according to Stevens and Walker (St 55), the ion at E = 6.2 Mev has a charge $Z^*_{av} = 4.84$ in a solid. These two measurements would indicate that the state of condensation effect is not significant. On the other hand, the measurements of Allison, Casson, and Weyl (Al 55) suggest that the dependence on the medium is very noticeable for ions of helium. According to Allison (private communication) the ratios of He^{++}/He^{+} for metals as measured by Allison, Casson, and Weyl are substantially higher than the corresponding values for air measured by Snitzer (Sn 53) and the ratios of He^{++}/He^{+} in metals measured by Dissanaike (Di 53) are substantially higher than the values obtained in gases by Snitzer and by Stier, Barnett and Evans (St 53). There is, however, some discrepancy between the values He^{++}/He^{+} in metals as obtained by Dissanaike and the corresponding values obtained by Allison, Casson, and Weyl.

In order to account for the state of condensation effect, Bohr

and Lindhard (Bo 54) suggested an explanation somewhat similar to the one given in connection with the "pressure effect". They assume that immediately after a collision a heavy ion has many of its orbital electrons in excited states and that the excitation energy of the electrons is not uniformly distributed. Some of the electrons have a relatively large excitation energy and it would require little additional energy in order to leave the ion. However, these excited electrons tend to readjust themselves so as to distribute their excitation energy more uniformly. Let T_{dis} be the time necessary for such a redistribution. The occurrence of the state of condensation effect depends upon the relative values of T_{dis} and T_{coll} in the same manner as the pressure effect depends upon the relative values of T_{exc} and T_{coll}.

For gases we have $T_{coll} > T_{dis}$ and, therefore, the excited ion distributed its excitation energy among several electrons before the next collision and the chance of having the ion further ionized is relatively small. For solids and liquids we have $T_{coll} < T_{dis}$ and, therefore, there is not sufficient time between two collisions to redistribute excitation energy and an electron originally placed in an excited state as a result of the first collision has a relatively large probability of being removed as a result of the next collision.

In order to apply the Bohr-Lamb theory to a condensed medium it would be helpful to know the distribution of electronic orbital velocities in an ion that is continually perturbed by collisions at a relatively high frequency. Such a study has not been made; therefore, another alternative would be to consider an empirical factor. Thus, Bohr and

Lindhard applied an empirical factor equal 3/2, i.e., they assumed that the average charge of a fission fragment in a solid is roughly 3/2 times larger than the corresponding charge in a gas. This factor, however, has a very limited region of applicability.

There is a question as to whether the model based on the Bohr and Lindhard theory is sufficient to take account of the state of condensation effect. According to Neufeld (Ne 54) the state of condensation effect may be due to a different process, i.e., to the reaction of the medium perturbed by the moving ion. This reaction causes a polarizing field and results in spontaneous emission of the orbital electrons. It is noted that Neufeld's explanation is applicable to any ion whereas the Bohr and Lindhard explanation is applicable only to heavy ions.

According to a recent suggestion of Neufeld and Snyder (Ne 57) the state of condensation effect in heavy ions has two contributing factors. One of these is due to the "close collisions" between the moving ions and the stopping atoms, and it accounts for a portion of this effect that is based on the Bohr and Lindhard explanation. The other factor is due to "distant collisions" and it represents mainly the integrated action of the medium on the moving ion. This other factor represents the portion of the effect that is based on the explanation of Neufeld. Therefore, in order to apply directly the Bohr-Lamb theory and to take account of the state of condensation effect one would need a model of an atom that is periodically perturbed and polarized in a strong electrical field. Such a model does not exist. Therefore, we have to follow the general procedure outlined by Knipp and Teller which

is based on a model of an ion in the ground state free of any external disturbance and see whether we can correct our results in order to account the effect of the medium by properly modifying the empirical parameter disturbance and to correct any discrepancy due to this model by means of an appropriate empirical parameter.

C. Empirical Parameters

We have introduced two parameters designated as γ_L and α_L. The parameter γ_L is similar to the parameter γ used by Knipp and Teller and by Brunings, Knipp, and Teller, i.e.,

$$\gamma_L = \frac{v_L}{V} \tag{8}$$

where v_L is the velocity of the most loosely bound electron having a binding charge $Z_L^* = Z_{av}^*$. The parameter α_L is such that

$$\alpha_L = \frac{Z_L^{*(1)}}{Z_{av}^*} \tag{9}$$

where $Z_L^{*(1)}$ is the binding charge that corresponds to the most loosely bound electron having velocity $v_L = V$. The subscript "L" indicates that the above values relate to the "Lisitzin graphs".

The values γ_L and α_L are shown in Table I for gaseous media and in Table II for condensed media. It is difficult to establish any

regularity in the behavior of either of these parameters. For many ion species the parameter γ_L or α_L seems to decrease with the increase of the velocity of the ion. However, this behavior is not sufficiently general.

Table III gives some general data regarding γ_L and α_L such as the maximum and minimum values for gases and condensed media, respectively. In this table we differentiate between "fission fragments" corresponding to Z = 38, 54, and "lighter ions" corresponding to Z = 3, 7, 8, 9, 10.

III. CORRELATION OF THE DMITRIEV THEORY WITH EXPERIMENT

The function $P(V/v_i)$ has been determined from the measurements of Stier, Barnett, and Evans (St 54), Stier and Barnett (St 56), and Barnett (Ba 57). These measurements are plotted in Fig. 8 showing $P(V/v_o)$ (where $v_o = e^2/\hbar$) for hydrogen beam moving in various gaseous media such as hydrogen, helium, oxygen, nitrogen, neon, and argon. We have neglected the occurrence of negative ions which are somewhat more numerous in argon for energies below 8 kev but are quite negligible for other gases. In the latter case the fraction of the total beam represented by the negatively charged ions is less than 2%. We have chosen for our computations the values $P(V/v_o)$ for the hydrogen beam in nitrogen since they represent the "average behavior". It is noted, however, that some of the curves shown in Fig. 8 depart considerably from the "average". The values v_i representing the orbital electronic velocities of neutral atoms have been taken from tables given by Slater (Sl 55). The dependence between the Z^*_{av} and the velocity V as predicted by the Dmitriev theory is plotted in form of graphs "D" in Figs. 1 to 6. It is noted that these graphs give values higher than those measured.

IV. THEORIES BASED ON CHARGE EXCHANGE COLLISIONS AND THEIR CORRELATION WITH EXPERIMENT

Bell (Be 53) has estimated the charge of a moving ion by considering more in detail the capture and loss processes due to the interaction with the surrounding medium. These processes can be described in the framework of classical mechanics provided no particular refinements are taken into account. By applying the statistical Thomas-Fermi model to heavy and light fission fragments, Bell has determined the functions $\sigma_L(Z^*, V)$ and $\sigma_C(Z^*, V)$ representing the loss and capture cross sections (for one electron) corresponding to a fission fragment having charge Z^* and velocity V. Neglecting the possibility of transferring two or more electrons in a single encounter, he assumed that the most probable and presumably the average ionic charge Z^*_{av} for a given velocity V can be determined from

$$\sigma_C(Z^*_{av}, V) \sim \sigma_L(Z^*_{av}, V) \tag{10}$$

The average charge of a fission fragment based on (10) has been computed by Bell and his values are shown in Table I. Table I shows also for comparison the experimental values obtained by Lassen (La 51; La 51a) and the values of Lassen modifed by Bell who took into account that his values of momenta of fission fragments exceed those of Lassen by 6%.

According to Gluckstern (Gl 55), the method used by Bell for calculating $\sigma_C(Z^*, V)$ should be modified in order to represent the capture

cross section for any electron and not the sum of individual capture cross sections as assumed by Bell. This modification will cause a decrease by about 40% of the value of the cross section calculated by Bell. Gluckstern questioned also the adequacy of a statistical model to describe the high charge states of a fission fragment and he modified Bell's method in order to make it particularly applicable to "light" ions (i.e., to ions having a relatively small nuclear charge Z). By replacing the Thomas-Fermi distribution by one in which the ion electrons are located in concentric shells with radii chosen to correspond to the known ionization potentials, Gluckstern determined the charge distribution for the ions of oxygen, neon and nitrogen in gases by means of the expression

$$N(Z^*, V)\, \sigma_L(Z^*, V) = N(Z^* + 1, V)\, \sigma_C(Z^* + 1, V)$$
$$\sum_{Z^*} N(Z^*, V) = 1 \qquad (11)$$

in which $N(Z^*, V)$ is the probability that the ion will have a charge Z^* at velocity V. The values of the average charge obtained by Gluckstern for oxygen and neon are in relatively good agreement with the experimental data of Hubbard and Lauer (Hu 55), the largest discrepancy being 0.3 of a unit charge. The values obtained by Gluckstern for nitrogen ions in gaseous media are somewhat smaller (by amounts varying from 0.2 to 0.4 of a unit charge) than the corresponding values for nitrogen ions that have been charge equilibrated in solids and measured by

Reynolds, Scott, and Zucker (Re 54), Reynolds and Zucker (Re 54a), and Reynolds, Wyly, and Zucker (Re 55a). According to Gluckstern, the model used in his computation is very crude and this discrepancy relating to the values of nitrogen ions should not be considered as a verification of the effect of the medium on the charge of the ion.

The expression (10) has also been used by Bohr and Lindhard (Bo 54) in estimating the charge of fission fragments and the agreement with the experiment was found satisfactory. However, the estimates of cross section for loss or capture are somewhat cruder than those of Bell.

The above methods based on the estimates of capture and loss cross section appear to have a better claim to accuracy than those involving the Bohr-Lamb criterion. However, there are no measurements of cross section for loss and capture covering any extended range of Z^* or V that could be used for comparison with the data obtained by Bell, Gluckstern, or Bohr and Lindhard.

V. FINAL REMARKS

We find it difficult not to express our disappointment that after surveying the literature covering the last sixteen years on correlating the proposed theories with experimental data, we are unable to reach a definite opinion regarding the accuracy of the proposed theories. This may be due to the great paucity of experimental data. Also because of a variety of measurement techniques the results may not be of uniform quality, and, therefore, comparison of data obtained by various experimenters may be difficult.

In order to assist further in this field we have prepared and assembled a set of graphs showing the "Lisitzin" and "Mayer" curves and data of Finkelnburg for those elements that have not been included in Figs. 1 through 7. This set of graphs is being issued as a supplement. (Supplement to ORNL-2365, 1957).

ACKNOWLEDGMENTS

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Table I

Parameters γ_L and α_L for Ions Passing through Gases

Ion Species	Stopping Medium	Reference	V/Z	γ_L	α_L
Oxygen	Argon	Hu 55	0.36	0.77	1.42
			0.49	0.71	1.29
			0.58	0.63	1.22
Neon	Argon	Hu 55	0.25	0.92	1.10
	(Hydrogen or Helium or Nitrogen or Argon)		0.38	0.80	1.38
	Argon		0.45	0.75	1.35
Strontium	Hydrogen	La 51 and 55	0.132	1.21	0.80
	Helium			1.09	0.92
	Nitrogen or Argon			1.23	0.78
	Hydrogen	Fu 57	0.145	1.07	0.90
	Helium			1.00	1.00
	Argon			1.12	0.85
	Hydrogen	La 51 and 55	0.158	1.16	0.84
	Helium			1.04	0.95
	Nitrogen			1.09	0.89
	Argon			1.12	0.87
	Oxygen			1.11	0.88
	Hydrogen	Fu 57	0.170	1.04	0.96
	Helium			0.95	1.07
	Argon			1.09	0.91

Table I cont.

Ion Species	Stopping Medium	Reference	V/Z	γ_L	α_L
Xenon	Hydrogen	La 51 and 55	0.055	1.35	0.88
	Helium			1.20	0.93
	Nitrogen			1.45	0.76
	Argon			1.44	0.77
	Hydrogen	Fu 57	0.061	1.18	1.15
	Helium			1.03	1.03
	Argon			1.31	0.77
	Hydrogen	La 51 and 55	0.074	1.22	0.73
	Helium			1.14	0.79
	Nitrogen			1.30	0.67
	Argon			1.37	0.63
	Oxygen			1.32	0.66
	Hydrogen	Fu 57	0.082	1.08	0.91
	Helium			1.03	0.97
	Argon			1.22	0.79

Table II

Parameters γ_L and α_L for Ions Passing through Solids

Ion Species	Stopping Medium	Reference	V/Z	γ_L	α_L
Lithium	Photographic emulsion	Ku 55	1.19	0.66	
			1.69	0.59	
	Celluloid	Te 57	0.61	0.67	1.26
			0.84	0.84	1.15
			1.22	0.23	
			1.83	0.52	
Nitrogen	Nickel	Re 54	0.23	0.75	1.66
			0.26	0.78	1.49
			0.34	0.76	1.37
			0.42	0.69	1.54
			0.49	0.70	1.29
			0.55	0.64	1.25
			0.61	0.59	1.19
			0.75	0.63	1.09
			0.82	0.64	1.10
			0.88	0.64	1.11
			0.98	0.66	1.24
			1.05	0.63	
			1.10	0.71	
			1.16	0.69	
			1.23	0.72	
			1.28	0.73	
	Formvar	Re 55	0.59		
			0.70		
			0.76		
			0.77		
			0.79		
			0.86		
			0.94		
			1.99		
			1.07		
			1.12		
			1.18		
			1.23		
	Nickel	Ko 55	0.16	1.06	0.88
			0.19	0.90	1.17
			0.21	0.85	1.33
			0.24	0.78	1.54
	Organic substance	St 55	0.86	0.65	1.11
			0.89		
		St 54	0.93	0.68	1.16
	Celluloid	Ni 57	0.24	0.97	1.06
			0.26	0.93	1.11
			0.36	0.84	1.28
			0.41	0.80	1.33
			0.54	0.68	1.16
			0.75	0.62	1.09

Table II cont.

Ion Species	Stopping Medium	Reference	V/Z	γ/L	α/L
Oxygen	Organic Substance	St 55	0.49 0.82	0.72 0.61	1.27 1.09
Fluorine	Organic Substance	St 55	0.72	0.55	1.15
Strontium	Mica Beryllium Aluminum Silver Uranium	La 51 and 55	0.132 0.158	1.61 1.51 1.49 1.48 1.36	0.55 0.61 0.63 0.64 0.67
Xenon	Mica Beryllium Aluminum Silver Uranium	La 51 and 55	0.055 0.074	2.09 1.96 1.94 1.90 1.86	0.45 0.39 0.40 0.41 0.43

Table III

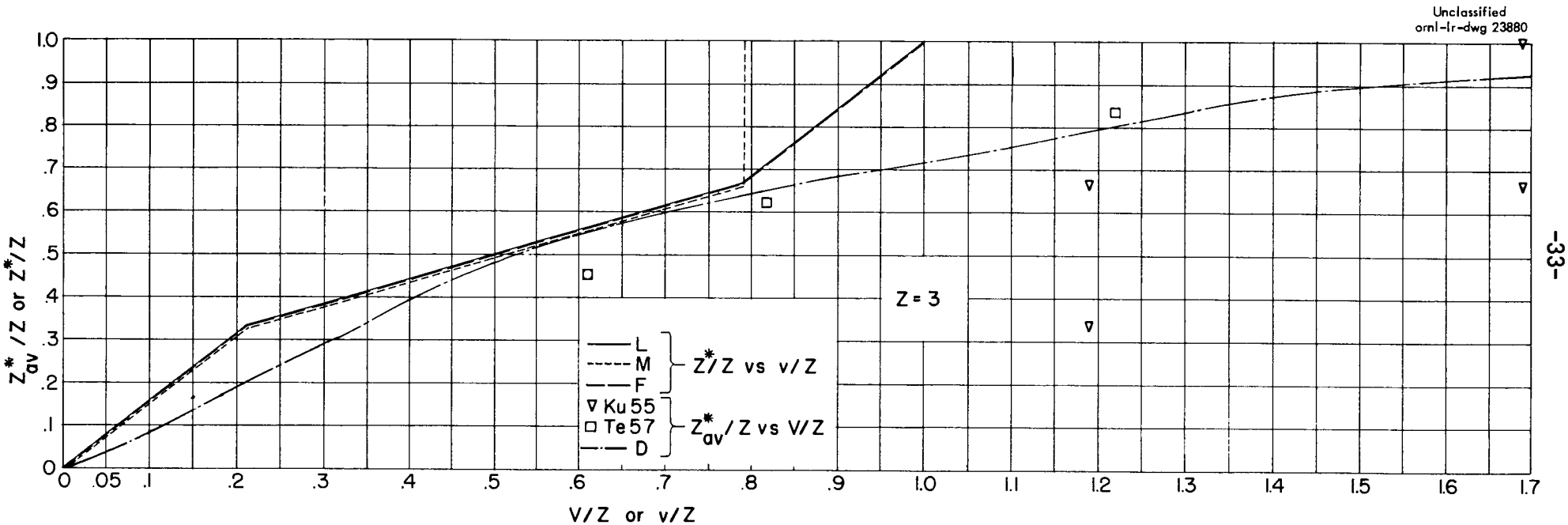
Dependence between the Parameters γ_L and α_L and the Character of the Medium

		Gases		Condensed Media	
		γ_L	α_L	γ_L	α_L
Fission Fragments	Maximum Value	1.45	1.15	2.09	0.67
	Minimum Value	1.03	0.63	1.36	0.39
Lighter Ions	Maximum Value	0.92	1.42	1.06	1.66
	Minimum Value	0.63	1.10	0.52	0.88

Table IV

Charges of Fission Fragments Obtained by Bell and by Lassen

Stopping Medium	Ion Species	Measurements of Lassen	Modified Values of Lassen	Values Calculated by Bell
Hydrogen	Light Fragment	15.8	16.7	22.5 (21)
	Heavy Fragment	12.6	13.3	16.3 (15)
Helium	Light Fragment	14.1	14.9	16.5
	Heavy Fragment	11.6	12.2	12.5
Oxygen	Light Fragment	15.2	16.1 ± 0.5	15.5
	Heavy Fragment	14.1	14.8 ± 0.5	13.5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V/Z or v/Z
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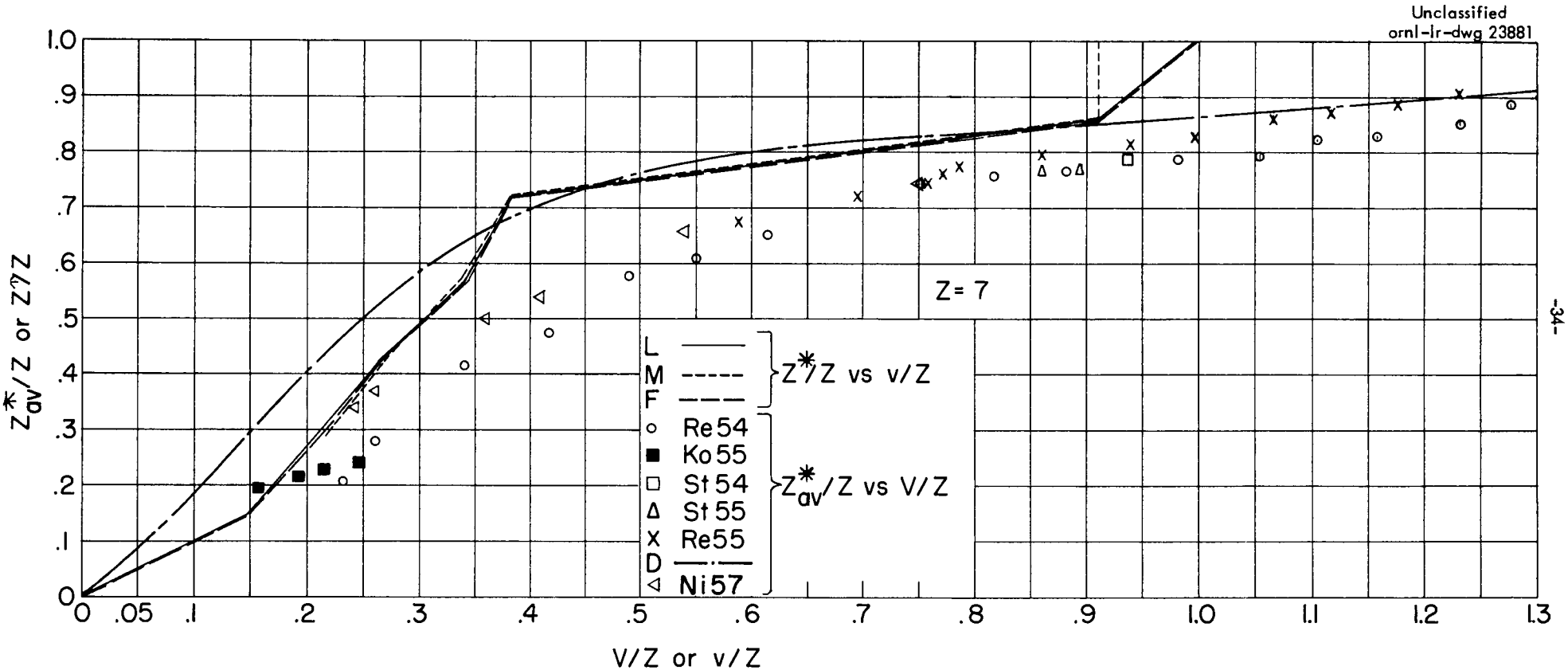
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Z*av/Z or Z*/Z
V/Z or v/Z
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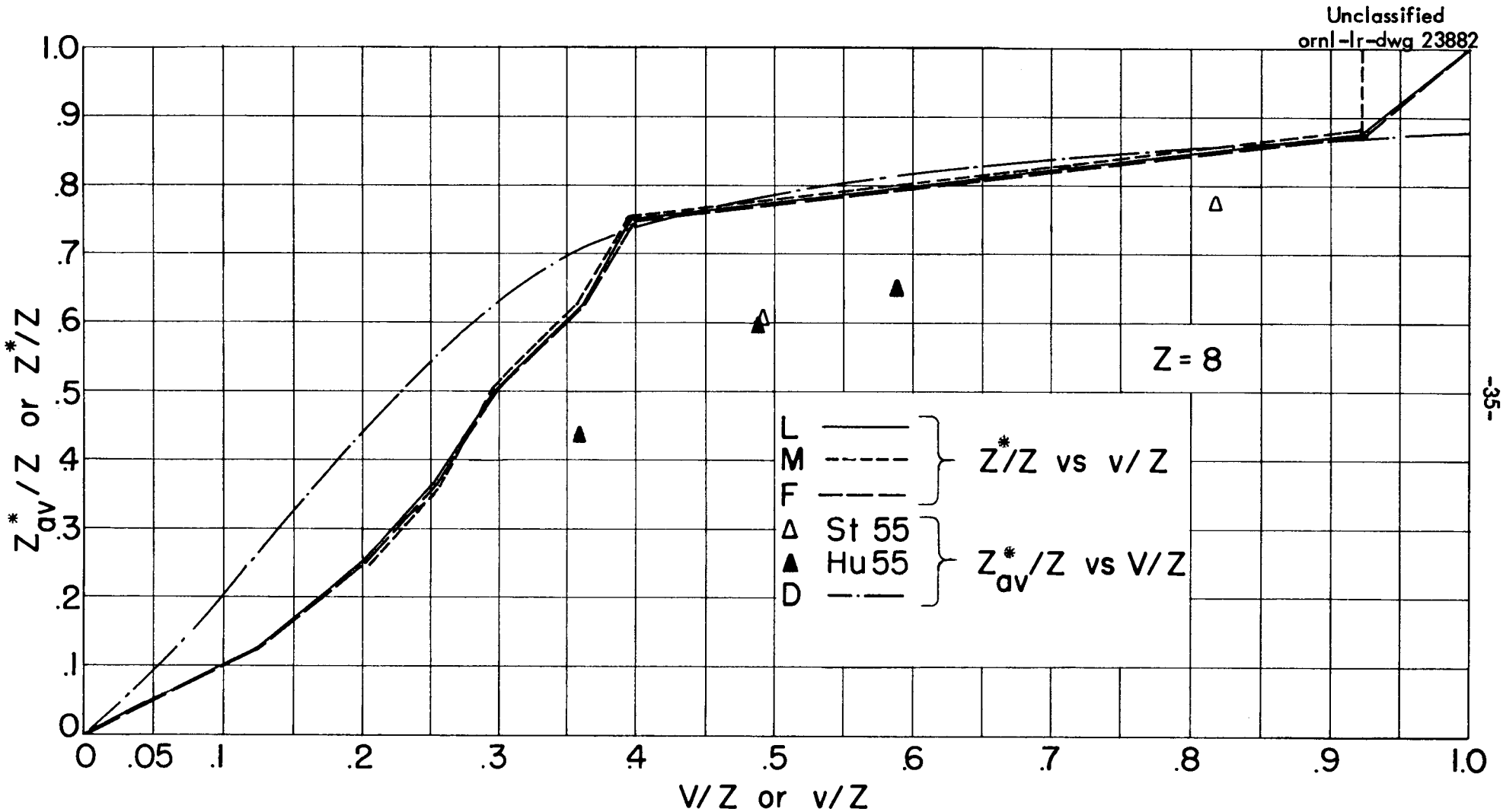
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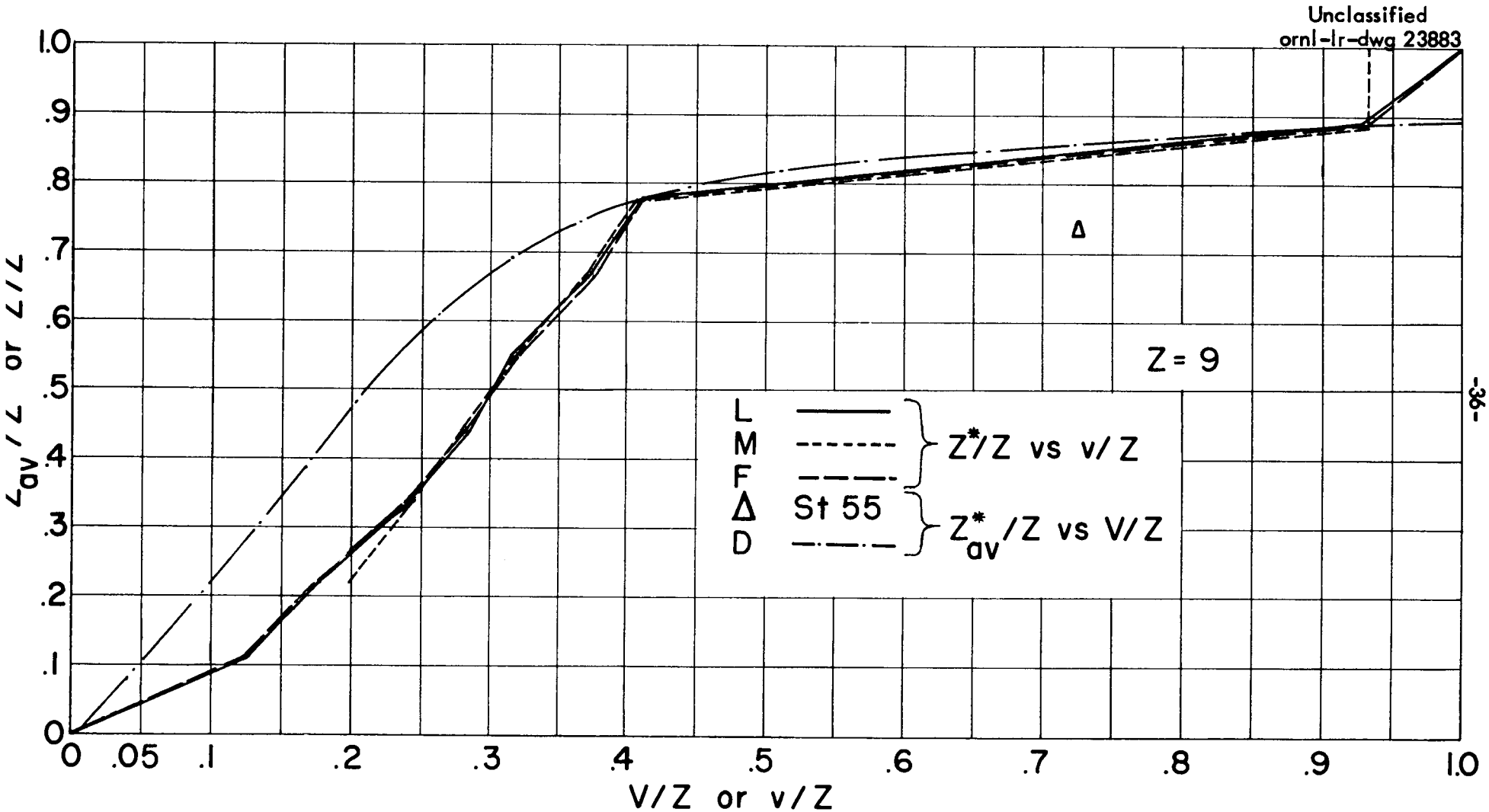
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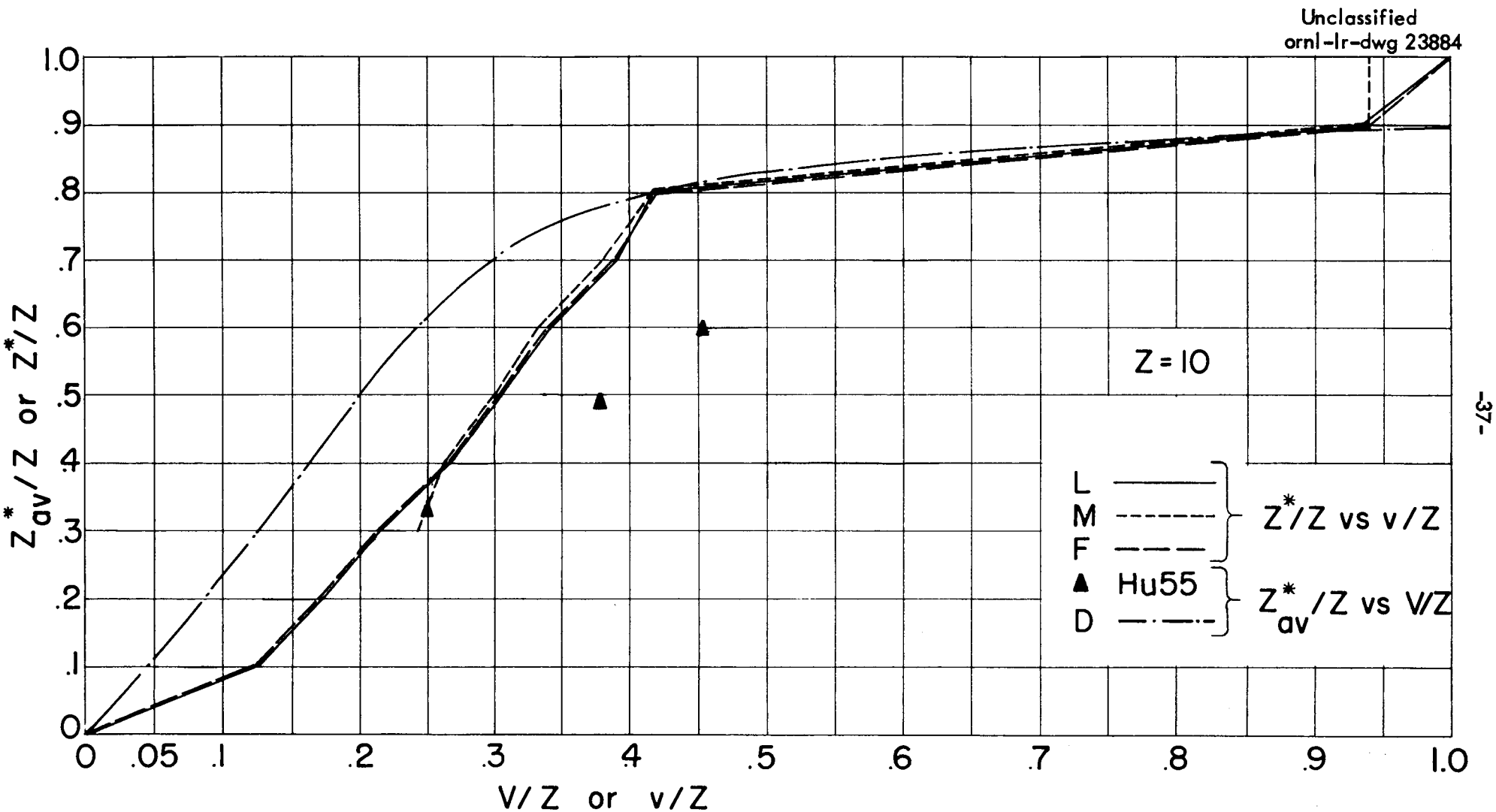
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.7
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F
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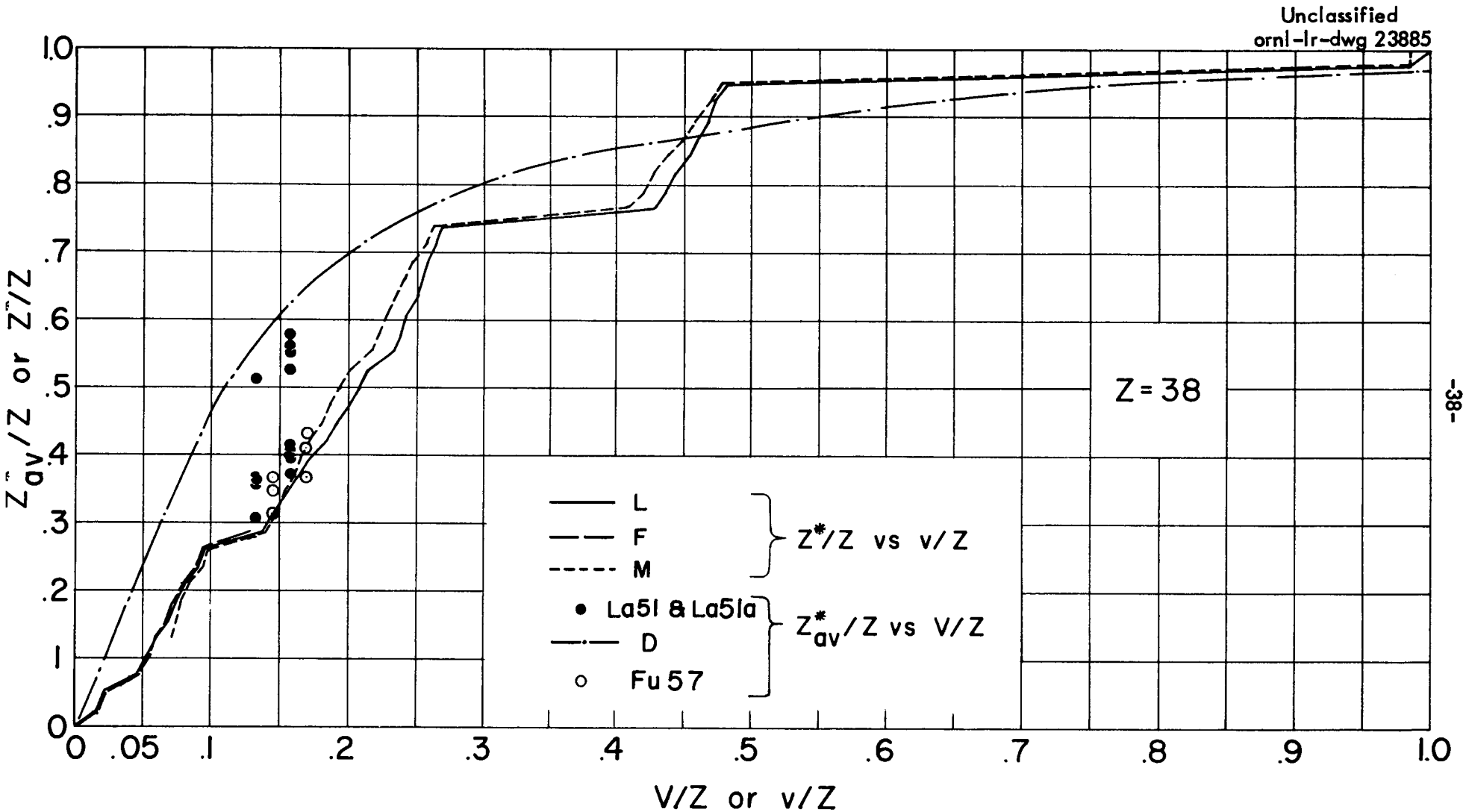
Hu55
D
Z^*_{av}/Z vs V/Z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Fu 57
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Z^*_{av}/Z or Z^*/Z
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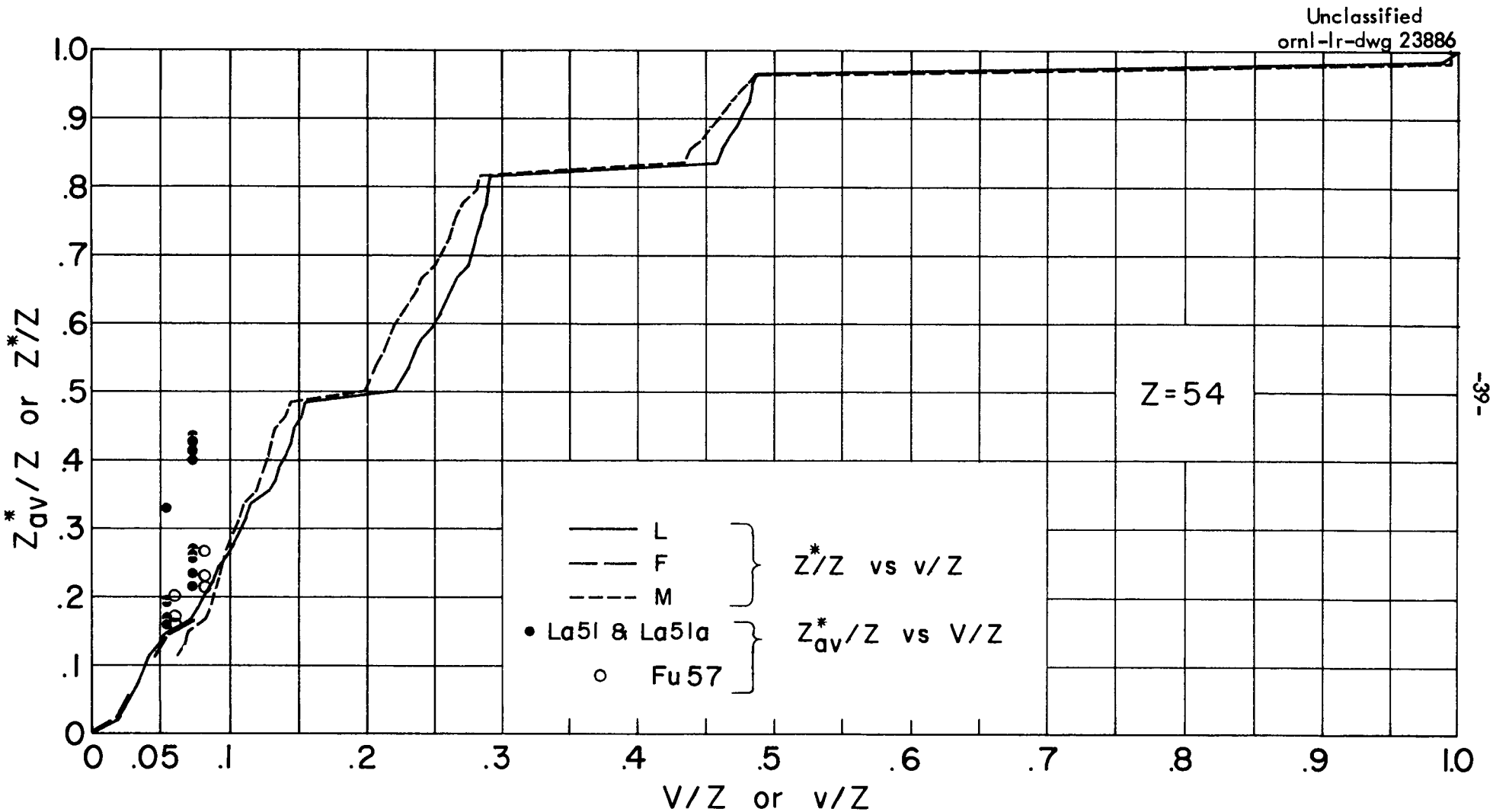
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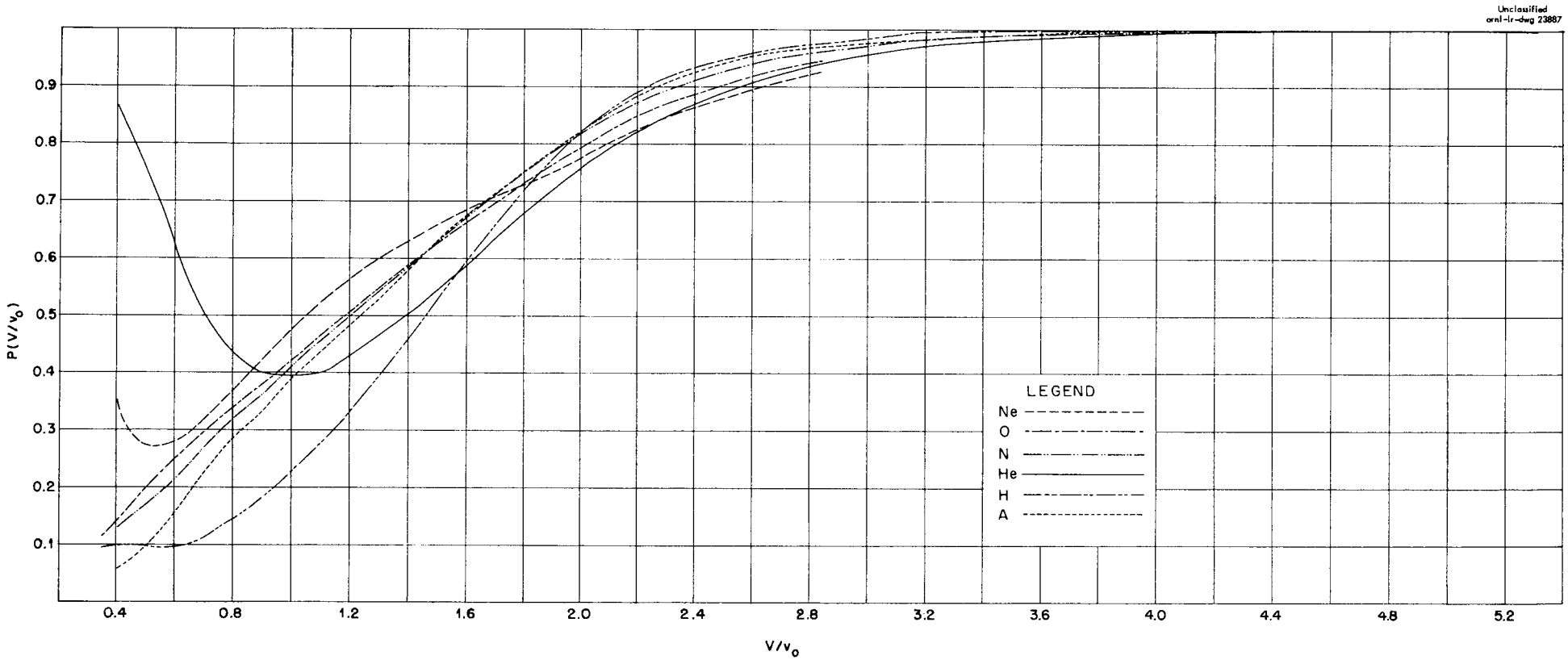
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V/v₀
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Ne
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N
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H
A

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