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STOPPING OF DYSPROSIUM IONS IN GASES AND ALUMINUM

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ABSTRACT

The stopping of Dy recoils of 6 to 21 MeV in D_2, He, N_2, Ne, A, Kr, and Xe has been studied by electrostatic collection. The range-energy data (along with previous results for Al and H_2) are compared with stopping theory. Range straggling due to the stopping process has been measured for the heavier gases. The magnitude of the electronic stopping has been estimated from range data, and independently from straggling data. These estimates suggest that electronic stopping cannot be adequately approximated as being proportional to velocity.

INTRODUCTION

The mechanism of energy transfer from a swiftly moving particle to its environment has been the subject of many theoretical and experimental investigations. Stopping studies and specifically the study of rates of energy loss by the swift particles, their range, and range straggling provide useful and convenient tests for various approximations used in the theoretical treatment of the interaction process. A working description of these properties is necessary for many devices used to identify moving particles or measure their energies. The state of knowledge, theoretical and experimental, is quite advanced for the energy loss of fully stripped ions of energy greater than 10 MeV/amu. The knowledge of stopping processes is very limited for partially stripped heavy ions of energy less than 1 MeV/amu. The theoretical treatment in this case is complicated by the necessity of taking into account ion-atom scattering and charge-exchange effects, in addition to ionization. Experimental studies suffer from the difficulty of obtaining appropriate particle sources.

This paper presents experimental measurements of the average range and range straggling of Dy ions of $\approx$ 6 to 21 MeV ($\approx$ 40 to 140 keV/amu) in various gases. These results, along with similar data for hydrogen and aluminum stoppers,[1,2] are compared with the theoretical calculations of Lindhard, Scharff, and Schiott[3].

This LSS theory is based on a statistical (Thomas-Fermi) model of the interacting atoms. Energy losses to electrons (ionization, or electronic stopping) and to atoms (ion-atom scattering or "nuclear" stopping) are considered as uncorrelated and continuous processes. The energy E_R and the range R of a particle of mass M_R and nuclear charge Z_R

stopped in a medium of atomic mass M_S and atomic number Z_S are represented respectively by the dimensionless variables

$$\epsilon = a M_S E_R / Z_R Z_S e^2 (M_R + M_S) \tag{1}$$

and

$$\rho_L = RNM_S \cdot 4\pi a^2 M_R (M_R + M_S)^{-2} \tag{2}$$

where

$$a = 0.8853 (\hbar^2 / me^2) (Z_R^{2/3} + Z_S^{2/3})^{-1/2} \tag{3}$$

is a Thomas-Fermi screening length, e and m the charge and mass of an electron, N the atomic density of the medium, and $\hbar$ Planck's constant, ~~and c the velocity of light~~.

The total reduced energy loss $(\frac{d\epsilon}{d\rho_L})$ is given as the sum of contributions from nuclear and electronic stopping,

$$(\frac{d\epsilon}{d\rho_L}) = (\frac{d\epsilon}{d\rho_L})_n + (\frac{d\epsilon}{d\rho_L})_e . \tag{4}$$

The electronic stopping is given approximately as

$$(\frac{d\epsilon}{d\rho_L})_e = k\epsilon^{1/2} , \tag{5}$$

with

$$k = \xi \left[\frac{0.0793 \; Z_R^{1/2} Z_S^{1/2} (M_R + M_S)^{3/2}}{(Z_R^{2/3} + Z_S^{2/3})^{3/4} M_R^{3/2} M_S^{1/2}} \right] ; \; \xi \approx Z_R^{1/6} \tag{6}$$

In this framework the range-energy relationship and range straggling for any projectile-stopper combination are characterized by the single parameter k. The theory should be applicable to all ions of velocity less than $\approx v_0 Z_R^{2/3}$ ($v_0 = 2.2 \times 10^8$ cm sec^{-1} is the Bohr orbital velocity

of the electron in hydrogen). The scope of this theory is clearly very broad and general, and the authors' intent is to present a generalized and comprehensive description rather than a set of detailed predictions for any particular case.

Our measurements provide a rather wide region for comparison with the theory. Recoil atoms of Dy were stopped in D_2, He, N_2, Ne, A, Kr, and Xe. Average ranges were determined in all materials for recoils of initial energies of ≈ 6 to 21 MeV. Range straggling due to stopping processes was measured for stoppers He through Xe. The general features of the results follow the trends of the theoretical outline.[3] More detailed comparisons reveal the areas where better approximations are desirable.

We have used nuclear reactions induced by heavy ions to provide the Dy recoil atoms. These reactions have been studied in some detail;[1,2,4] the width of the initial velocity distribution is known,[1,4] and a correction for its effect on the observed range distributions has been made. This correction is not significant for the determination of average range as a function of energy in any stopping material.[2] The correction to the observed range straggling is not severe for the stopping gases N_2, Ne, A, Kr, and Xe. Therefore, this study provides data for both range and range straggling as a function of energy in these systems. Previous studies have not been able to obtain satisfactory measurements of range fluctuations in noncrystalline media.

II. EXPERIMENTAL METHOD

These measurements were made with the same apparatus and following the same procedures as described in the preceding paper.[1] There are several differences between the behavior of hydrogen gas as previously described and the behavior of the rare gases and N_2 used in this work. Our major concerns are the effects of diffusion and convection on the "range distributions" that we observe. The relationships of importance to these effects are the diffusion distance $\langle x^2 \rangle^{1/2}$,

$$\langle x^2 \rangle^{1/2} = [Dt]^{1/2} \tag{7}$$

and the average drift velocity $\bar{v}$ of an ion,

$$\bar{v} = EqD/kT , \tag{8}$$

where D is the diffusion coefficient, t is the time required for collection, E is the electric field, q is the charge of the ion, k is Boltzmann's constant, and T is the absolute temperature.

For hydrogen gas the possibility of collecting neutral atoms on the negative plate could be excluded, because of the ratio of ten to one in the collection efficiency of negative and positive plates. The possibility of a long collection time ($t \gtrsim 0.04$ sec), resulting from neutralization and reionization, was excluded by observing the width of the range distribution in H_2 as a function of collection time. (Electric field, pressure, and distance between collector plates were varied, with negligible effect on the width of the range distribution for average ranges of 4 to 6 in.)

The situation is somewhat different for the series of rare gases He, Ne, A, Kr, and Xe. (The behavior of N_2 is intermediate between that of H_2 and the rare gases.) The estimated values of the diffusion coefficients of Dy are essentially the same for all gases involved, if the pressures are adjusted to give equal average ranges (in units of length) for any given initial recoil energy.[5] Thus the time required to collect an ion in H_2 or rare gases is of the order of 10^{-4} sec. However, the hot atom chemistry, neutralization, and reionization, are not the same in H_2 and the rare gases. This is demonstrated by the fact that in rare gases Dy recoils are about equally distributed between positive and negative collectors (compared to very little negative-ion collection in H_2). The range distributions in rare gases at the two oppositely charged plates are essentially identical, and the total collection efficiency is 60 to 90% with electric fields of $\gtrsim$ 50 volts/cm or more. Experiments in He with no electric field show the same average range (within 5%) as with an electric field, but the width of the distribution is about 50% greater for zero field. Also the collection efficiency is about 1/10 as large, indicating a low probability for collecting neutral atoms or molecules. Presumably the neutral atoms or molecules are swept away from the collector plates by convection currents. These observations are consistent with the notion that the lifetime of Dy as a positive or negative ion is long enough for electrostatic collection to take place, and that diffusion of the collected ions plays a minor role. If this is indeed the case then the range distribution in the rare gases should be independent of electric field, pressure, and interplate distance, as with H_2. Experimentally this situation is observed for He as shown in Table I.

The application of the field and distance tests for the heavy rare gases is not as straightforward as in hydrogen. The reasons for this are twofold: (a) the plate voltage necessary to induce discharge in the chamber is about 400 volts for Kr or Xe at a pressure of 1 in. of Hg, (b) and owing to scattering of recoil Dy atoms by Kr or Xe, there is a finite probability of the recoils' hitting the collector plates before being actually stopped in the gas. Thus for ranges of about 4 in. we were forced to collect in Kr and Xe with an interplate distance of 3 in. and about 250 volts on each plate, and it was not possible with our chamber to obtain meaningful distance or field tests in Kr or Xe.

We were able to measure the range distributions in A, Kr, and Xe for several pressures. These measurements show that the fractional width of the range distribution -- i.e. its standard deviation divided by the median range -- is essentially independent of pressure.[6] This result strongly suggests that diffusion can indeed be neglected, as argued previously. Actually, we could have anticipated that the effect of diffusion would be less serious in Xe than in He because the diffusion coefficients are comparable whereas the range straggling due to stopping processes is much greater in the heavier gas. Also, the slightly troublesome short-range tail observed for the narrow range distributions in hydrogen is not even visible for the wide range distributions in Xe.

At a given beam intensity, say 75 mμA, the upward displacement of the collected atoms due to convection is an increasing function of the atomic weight of the stopping gas. Nevertheless, we have not been able to detect a broadening in the width of the horizontal distribution that is correlated with this convection effect (or beam intensity). The possibility of convection effects has been minimized by bombarding with average beam currents of less than about 50 mμA.

Our conclusion is that in spite of differences between the recoil collection in H_2 and the rare gases, the observed range distributions are not significantly affected by diffusion or convection in all gases, and represent true projections of the actual recoil range distributions in the gas.

III. RESULTS

The results of our experiments for gases other than H_2 are given in Table I, and some graphical displays are shown in Figs. 1 and 2. Results for stopping in hydrogen and Al are given elsewhere.[1,2] The beam energy (10.38 MeV/amu initially) was calculated from the energy-loss data of Northcliffe[7] and the carefully measured thicknesses of Al foils and stopping gas. The average recoil energy E_R is related to the beam energy E_b by[2]

$$E_R = E_b A_b A_R/(A_b + A_T)^2 , \qquad (9)$$

where A denotes mass number, with subscripts b, R, and T for bombarding particle, recoil, and target atoms, respectively. R_0 is the median range as obtained from a probability plot of the range distribution corrected for energy loss in the target. It is compared, in column 7, with the average range $\langle R \rangle$ as calculated from the actual distribution, and the deviation usually does not exceed 1 to 2%. Values of R_0 will be used throughout the rest of the paper. These values were converted to mg/cm^2 by using the measured pressures and assuming a constant temperature of 20°C. No attempt was made to determine the actual ambient temperature during the experiment, since this temperature does not reflect transient local heating of the gas by the passing beam. Such local heating effects have been observed by Martin and Northcliffe.[8] This temperature uncertainty is probably the largest single source of error in the range values, and we estimate this error to be of the order of 2 to 3%.

The measured range straggling parameter, ρ (column 6), is obtained from the probability plots, in terms of relative standard deviation, i.e., $\rho = \frac{\sigma}{R_0}$. Column 8 gives the ratio of the standard deviation calculated from the actual distribution to that obtained from the probability plot. This ratio is almost invariably > 1, even when the probability plot shows essentially no tail. This difference apparently reflects scatter of the experimental points due to counting statistics, strip width variation, etc., which are omitted by the graphical procedure. The ratio of column 8 is also increased by a substantial short-range tail.

Columns 9 through 11 show the ratio of the cumulative fractional activity to that predicted by the Gaussian fits, at ranges $R_0 - \sigma$, $R_0 - 2\sigma$, and $R_0 + 2\sigma$. The correlation between columns 8 and 10 is quite apparent. As discussed in the preceding paper,[1] we feel that the "short range tails" for H_2, D_2, and He are largely of instrumental origin. This may not be so for the wide distributions in the heavier gases but there the differences are less significant. Values of ρ as obtained from the Gaussian fits will be used throughout the rest of the paper.

Finally, the last column of Table I gives the values of the straggling parameter ρ_s due to the stopping processes

$$\rho_s^2 = \rho^2 - \rho_n^2 \qquad (10)$$

The measured straggling parameter ρ has been corrected for the straggling ρ_n due to the initial velocity distribution. The values of ρ_n are almost the same as the straggling observed in H_2 (or D_2).[1] Values of ρ_s are more accurate for the heavier gases because the correction becomes less important.

IV. DISCUSSION

The rather extensive range-energy data for stopping of Dy (and Tb) in H_2 and Al are shown in Fig. 3. The rate of increase of experimental ranges with energy is somewhat less than the theory predicts. Smooth fits to these data were obtained by the method of least squares with an equation of the form

$$R_0 = a_0 + a_1 E_R + a_2 E_R^2 , \qquad (11)$$

as discussed in detail in the preceding paper.[1]

Differentiation of the range-energy curve (Eq. 11) leads to the energy loss $\frac{dE_R}{dR_0}$ (or $\frac{d\epsilon}{d\rho_L}$). From Eq. (4) and values of energy loss due to nuclear stopping $(\frac{d\epsilon}{d\rho_L})_n$ as calculated by Lindhard,[3] it appears that over the energy range of these experiments $(\frac{d\epsilon}{d\rho_L})_e > (\frac{d\epsilon}{d\rho_L})_n$, so that by subtraction we can get a good approximation to the electronic stopping. These various energy loss values are shown in Fig. 4. It is clear that electronic stopping increases with energy more rapidly than $k\epsilon^{1/2}$, and therefore the range must increase less rapidly with ϵ than the calculations predict.

Our data for stopping gases other than H_2 are not extensive enough for accurate differentiation. However, the comparison of the experimental ranges with the theory for recoils of about 6, 8, 14, and 20 MeV reveals a similar trend for all gases. Figure 5 shows the comparison, and later in Table II the results are clarified.

A more detailed look at Fig. 4 seems to indicate somewhat different trends for energy losses in Al and H_2. In Al the slope of the curve appears to be ≈ 0.67, while in H_2 the slope seems to increase from ≈ 0.56 to ≈ 0.96.

The absolute magnitude of these slopes is subject to large errors and should not be taken too seriously, but the deviation of both from a slope of 1/2 is clear. It is also significant that similar deviations from the $k\epsilon^{1/2}$ rule for electronic stopping have been observed for the stopping of He^4, Li^7, C^{12}, N^{14}, and Ne^{20} in various gases and metals.[9-11] All these data point toward the desirability of a more detailed theoretical description of electronic stopping. Gryzinski has shown that whenever the velocity of the moving ion is of the same order of magnitude as the velocity of orbital electrons in the stopper, the energy loss depends strongly on details of the electron density distribution in the stopper, and statistical treatments can no longer be strictly applied.[12] The reasonable fit of the ranges of fission fragments to an empirical equation of the form $R = CE^{1/2} + \Delta$ has been quoted as evidence for the proportionality of electronic stopping to $\epsilon^{1/2}$. However, Alexander and Gazdik have shown that equally good fits for both Tb recoils and fission fragments in Al are obtained with an $R = KE^{2/3}$ form,[13] and the data can also be fitted to an equation $R = \alpha E^{1/3} + \beta$, which is equivalent to the slope of 0.67 mentioned above. More precise and extensive data are necessary to determine the exact functional dependence of electronic stopping on velocity and stopping material.

Figure 6 shows some of the data of Figs. 3 and 5, along with the ranges of fission fragments.[14-16] In Al, for which data on degraded fission products are available,[14] ranges of Dy recoils and heavy and light fission fragments can be compared for overlapping values of reduced energy ϵ. The three sets of data are consistent, and the agreement with theory appears to improve at higher velocities. In gases, reliable data are available only for full-energy fission fragments, and the comparison is more difficult. The

general trend is similar for all gases: the reduced range (ρ_L) increases by less than the predicted amount between $\approx$ 21-MeV Dy recoils and $\approx$ 65-MeV heavy fission fragments. Between the heavy and the light fission fragments the increment of the reduced range appears to agree with the theory.

The data are not extensive enough to distinguish between the following different interpretations of these results:

(a) The increase of electronic stopping, $(d\epsilon/d\rho_L)_e$, as a function of the reduced energy ϵ is much more pronounced than predicted by Eq. (5) for values of ϵ up to $\approx$ 50. For values of ϵ between 50 and 500, Eq. (5) is reasonably accurate. This inflection may be related to the maximum of electronic stopping around the ion velocity $v_1 = v_0 Z_R^{2/3}$.

(b) Equations (1) through (6) give only an approximate description of the dependence of energy loss on the mass and charge of the projectile, and the comparison between Dy recoils and light fission fragments is not strictly valid.

(c) Since the experimental conditions of our measurements differ considerably from those of the fission fragment experiments, we cannot exclude the possibility of systematic differences between the two sets of data. If our ranges in gases were systematically higher, by 20 to 30%, than those obtained for the fission fragments, the apparent difficulties would be removed. Such a systematic difference might, for example, be due to ionization of the gas by the bombarding beam. However, the estimated fraction of ionized gas molecules appears to be too small to affect our results.

The range straggling is very sensitive to the relative magnitudes of nuclear and electronic stopping. At these energies the fluctuations in electronic stopping should be very small with respect to those in nuclear stopping.[3] In Fig. 7 we compare our range straggling data with the theo-

retical calculations of Lindhard et al. The observed energy dependence is very similar to that given by the theory, and, in fact, the absolute magnitudes of the predicted straggling parameters (ρ) are within $\approx$ 60% of the measured values. As in the case of the median range, however, the straggling increases less rapidly with energy than indicated by the theory, and the approximate nature of the $k\epsilon^{1/2}$ dependence of the electronic stopping is again revealed.

Let us adopt the attitude that the major defect of the theoretical framework is this assumption of proportional dependence of electronic stopping on the velocity of the particle. Then we can regard k as an adjustable empirical parameter, weakly dependent on energy, and leave the rest of the theoretical treatment intact. If this approach has value, and the main body of the theory is indeed self-consistent, then the empirical values of k from two independent sources (R_0 and ρ) should agree. In Table II we give a comparison of the two sets of empirical values of k, along with theoretical values, as given by Eq. (6). Since empirically k increases with energy for each stopping material, the lower value is for recoils of $\approx$ 6 MeV, and the higher one for $\approx$ 21 MeV. For stopping in gases the agreement of k values from the range and range-straggling data is very close, except for 6-MeV recoils stopped in Kr and Xe. For these cases the correction factor for the difference between the mean projected range and the actual path length is quite large, and the discrepancy may be related to uncertainties in the calculated magnitude of this correction factor or to the approximate nature of the assumption $\Delta R^2_p = \Delta R^2$ (the variance of the projected range distribution equals that of the actual one).[3] In Al, and especially at the higher energies, the

empirical k values are not in agreement. We cannot be certain whether this is an experimental difficulty due to foil inhomogeneities, or a genuine stopping property, possibly related to Lassen's observation that the ionic charge distribution of fission fragments emerging from a solid is much broader than that from a gas.[17]

The absolute magnitudes of the empirical k values provide another argument for the desirability of a more detailed theoretical description of the electronic stopping process. Contrary to simple theoretical predictions, the mass stopping power is not a monotonic function of the atomic number of the stopping material, and rather large fluctuations are observed, especially in the light elements, for which the statistical model is expected to be least valid. Only in H_2, D_2, and Al does the average experimental value of the parameter k agree with that obtained from theory. In all the other gases the experimental electronic stopping power is considerably smaller than the theoretical one (a factor of more than 2 in Ne). In its present formulation the theory does not take into account any dependence of the energy loss on the density of the stopping medium.[17-19] The difference in electronic stopping between Al and Ne or A may be caused, partially at least, by different states of condensation. In addition, possible effects of ionization of the gas by the beam should also be considered. The deviations from theory of empirical k values as determined from the fission product ranges of Fig. 6 are smaller than in our case (except for H_2 and D_2) although not negligible. Further experimental study would be necessary to clarify this point.

SUMMARY

This study of range and range straggling of Dy ions in a variety of stopping media provides detailed tests of some of the approximations used in stopping theory. The measured ranges are all within about 30%, and range straggling parameters within about 60% of theoretical estimates. Both range and straggling data suggest departures from the approximation of proportionality of electronic stopping to velocity.

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FOOTNOTES AND REFERENCES

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Table I. Stopping of Dy ions in gases.

E_R[a] (MeV)	Pressure (in. Hg)	Field[b] (volts/in.)	R_o (in.)	R_o (mg/cm^2)	ρ	$\frac{\langle R \rangle}{R_o}$	$\frac{\langle \Delta R^2 \rangle^{1/2}}{\langle R \rangle \rho}$	$\frac{F(R_o-\sigma)^c}{F_G}$	$\frac{F(R_o-2\sigma)^c}{F_G}$	$\frac{F(R_o+2\sigma)^c}{F_G}$	ρ_s
					Deuterium						
5.82[1]	5.40	2000/2	4.81	0.370	0.135	0.994	1.04	1.00	1.76	1.00	d
8.29[2]	10.00	2000/2	3.33	0.474	0.126	0.983	1.30	1.22	2.86	1.00	d
14.18[3]	13.61	2000/2	3.78	0.731	0.095	0.993	1.24	1.00	1.62	1.00	d
20.65[4]	17.05	2000/2	3.89	0.943	0.090	0.998	1.18	1.06	1.85	0.98	d
20.68[4]	16.76	2000/2	3.99	0.951	0.087	0.998	1.15	1.00	1.45	0.99	d
20.79[5]	17.05	2000/2	3.90	0.944	0.088	0.998	1.18	1.06	1.85	0.98	d
					Helium						
5.80[1]	7.58	1000/2	4.24	0.453	0.157	1.000	1.08	1.00	1.41	1.00	0.074
7.96[2]	10.68	2000/2	3.70	0.556	0.170	0.998	1.03	1.00	1.27	1.00	0.105
7.96[2]	10.70	1500/3	3.67	0.552	0.156	0.993	1.03	1.00	1.14	1.00	0.081
7.96[2]	10.74	1000/2	3.70	0.559	0.165	0.998	1.05	1.00	1.41	1.00	0.097
14.15[3]	16.10	1600/2	4.13	0.938	0.118	0.996	1.07	1.00	1.14	1.00	0.071
20.65[4]	20.55	2000/2	4.29	1.243	0.100	0.998	1.08	1.00	1.62	1.00	0.062
					Nitrogen						
5.82[1]	0.99	1000/2	4.66	0.465	0.213	0.994	1.01	1.00	1.17	0.98	0.162
8.53[6]	1.80	2000/2	3.96	0.699	0.143	0.992	1.13	1.13	2.48	0.99	0.111
14.15[3]	2.77	1500/2	3.56	0.973	0.139	0.993	1.06	1.00	1.30	1.01	0.102
20.65[4]	3.47	2000/2	3.72	1.277	0.109	0.999	1.12	1.02	1.42	1.00	0.075
					Neon						
5.77[1]	3.17	400/2	2.52	0.571	0.253	0.996	1.07	1.05	1.48	0.99	0.212
7.70[2]	6.05	400/2	1.72	0.739	0.230	1.001	1.05	1.00	1.38	1.00	0.189
14.13[3]	4.71	500/2	3.80	1.272	0.168	0.990	1.05	1.01	1.55	1.01	0.139
20.56[4]	5.90	600/2	4.11	1.724	0.152	0.981	1.15	1.10	1.86	1.00	0.130

Table I. (Cont'd)

E_R[a] (MeV)	Pressure (in. Hg)	Field[b] (volts/in.)	R_o (in.)	R_o (mg/cm^2)	ρ	$\frac{\langle R\rangle}{R_o}$	$\frac{\langle \Delta R^2\rangle^{1/2}}{\langle R\rangle \rho}$	$\frac{F(R_o-\sigma)^c}{F_G}$	$\frac{F(R_o-2\sigma)^c}{F_G}$	$\frac{F(R_o+2\sigma)^c}{F_G}$	ρ_s
					Argon						
5.77[1]	1.85	600/2	2.32	0.606 .46	0.264	0.995	1.06	1.04	1.45	1.00	0.225
5.82[1]	1.13	600/2	3.69	0.588	0.268	0.989	0.985	1.00	1.00	1.01	0.230
14.13[3]	2.83	600/2	3.26	1.299	0.166	0.991	1.11	1.15	2.14	1.01	0.137
14.24[3]	1.75	600/3	5.35	1.320	0.166	0.993	1.07	1.05	1.70	1.01	0.137
20.24[4]	4.87	1200/2	2.43	1.665	0.146	0.984	1.25	1.27	2.95	1.00	0.123
20.70[4]	2.74	1200/2	4.35	1.677 1.4	0.151	0.991	1.05	1.09	1.59	1.01	0.129
					Krypton						
5.79[1]	1.11	500/2	2.46	0.807	0.310	0.993	1.05	1.00	1.00	1.00	0.279
5.81[1]	0.82	600/3	3.39	0.821	0.302	0.998	1.01	1.00	1.06	1.00	0.278
14.18[3]	1.56	600/2	3.75	1.727	0.218	0.985	1.07	1.12	1.86	1.01	0.197
20.25[4]	3.22	800/2	2.40	2.278	0.183	0.990	1.06	1.10	2.05	1.01	0.165
20.70[4]	1.80	800/2	4.21	2.235	0.198	1.010	1.12	1.28	2.90	1.00	0.182
					Xenon						
5.79[1]	0.78	500/2	2.48	0.896	0.310	0.993	1.05	1.00	1.14	1.00	0.277
5.81[1]	0.56	600/3	3.44	0.893	0.319	0.999	1.01	1.00	1.00	1.00	0.288
14.21[3]	1.03	500/2	3.86	1.844	0.249	0.988	1.08	1.10	1.74	1.01	0.231
20.32[4]	2.21	1000/2	2.37	2.419	0.185	0.980	1.16	1.24	2.50	1.00	0.168
20.76[4]	1.22	600/3	4.47	2.520	0.194	0.994	1.02	1.09	1.32	1.00	0.177
20.91[5]	1.22	600/3	4.46	2.515	0.218	0.994	1.02	1.00	1.03	1.00	0.200

[a]Based on the following reactions

1. $Nd^{144}(C^{12},5n)\ Dy^{151}$
2. $Nd^{144}(C^{12},7n)\ Dy^{149}$
3. $Ce^{140}(O^{16},7n)\ Dy^{149}$
4. $Ba^{138}(Ne^{20},9n)\ Dy^{149}$
5. $Ba^{138}(Ne^{20},8n)\ Dy^{150}$
6. $Ce^{140}(O^{16},5n)\ Dy^{151}$

[b]The potential difference divided by distance between plates.

[c]F denotes the cumulative fractional activity corresponding to ranges of less than $R_o-\sigma$, $R_o-2\sigma$, or greater than $R_o+2\sigma$. Subscript G refers to the Gaussian straight line of the probability plot.

[d]Not calculated (straggling dominated by the nuclear reaction).

Table II. The values of the parameter k.

Stopping gas	Theoretical	Empirical	
		From ranges[a]	From straggling
H_2	0.15	0.14 - 0.17	
D_2	0.11	0.09 - 0.12	
He	0.11	0.05 - 0.09	0.055
N_2	0.11	0.07 - 0.09	0.065 - 0.085
Ne	0.11	0.04 - 0.06	0.04 - 0.05
Al	0.11	0.08 - 0.12	0.07 - 0.08
A	0.11	0.07 - 0.10	0.075 - 0.95
Kr	0.14	0.06 - 0.11	0.09 - 0.10
Xe	0.16	0.09 - 0.14	0.12 - 0.14

[a]Based on range data corrected for the difference between true and projected ranges.

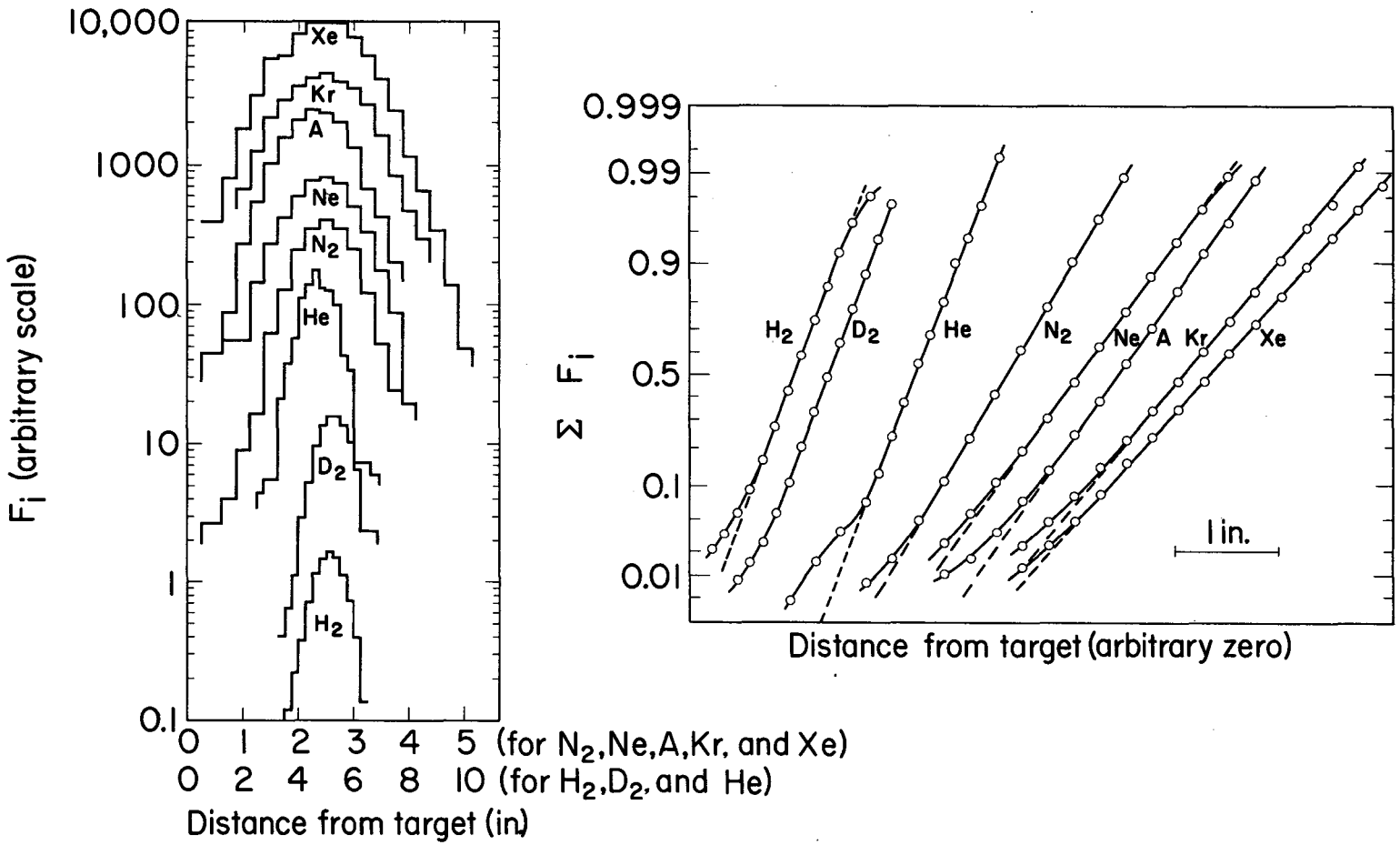

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Fig. 1. Differential range histograms and probability plots for studies of Dy recoils produced by the reaction $Nd^{144}(C^{12},5n)Dy^{151}$ at 78 MeV. (F_i denotes the fractional activity on the ith 1/4-in. strip, ΣF_i denotes the cumulative fractional activity through the ith 1/4-in. strip.)

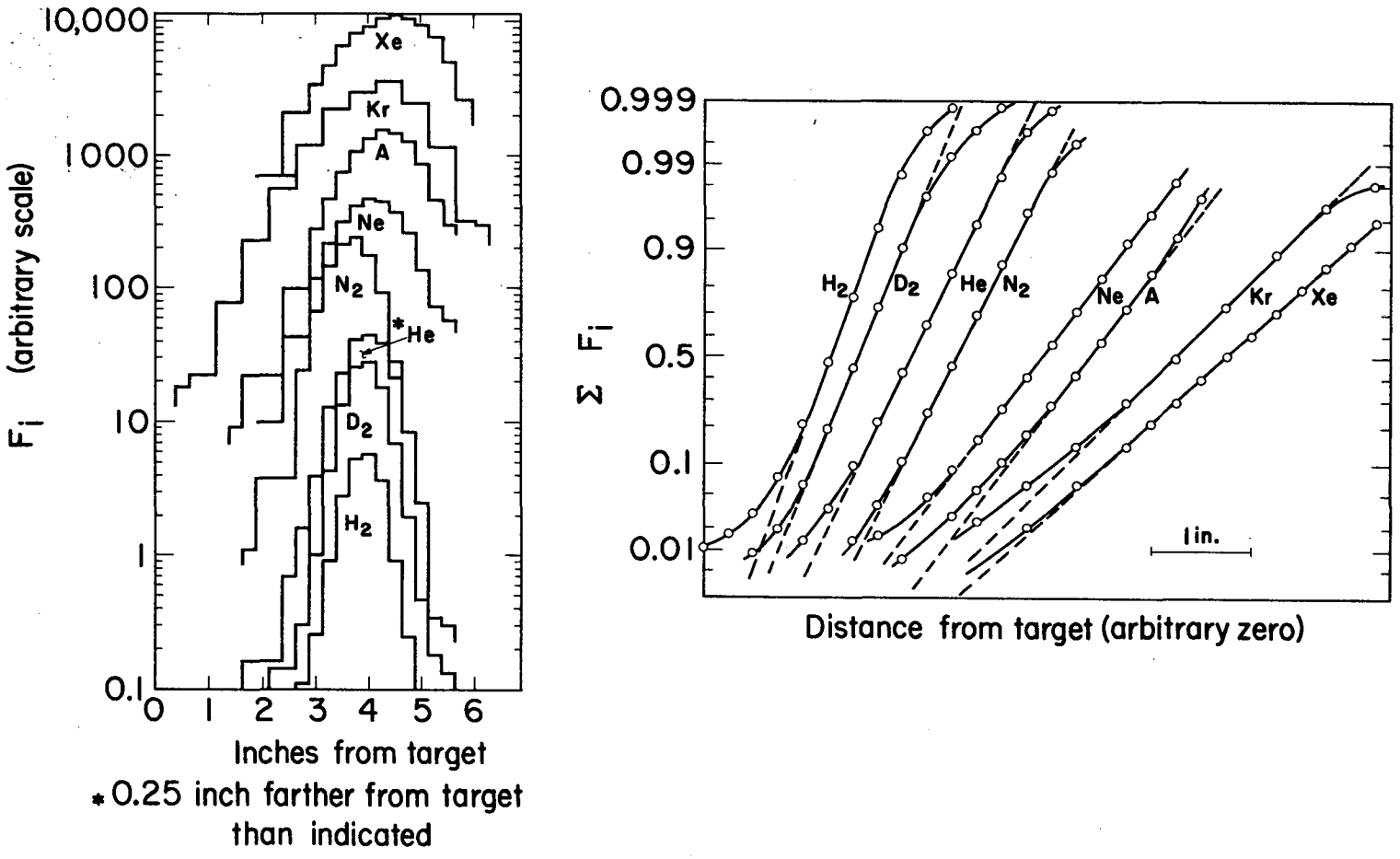

Fig. 2. Differential range histograms and probability plots for studies of Dy recoils produced by the reaction $Ba^{138}(Ne^{20}, 9n)Dy^{149}$ at 170 MeV.

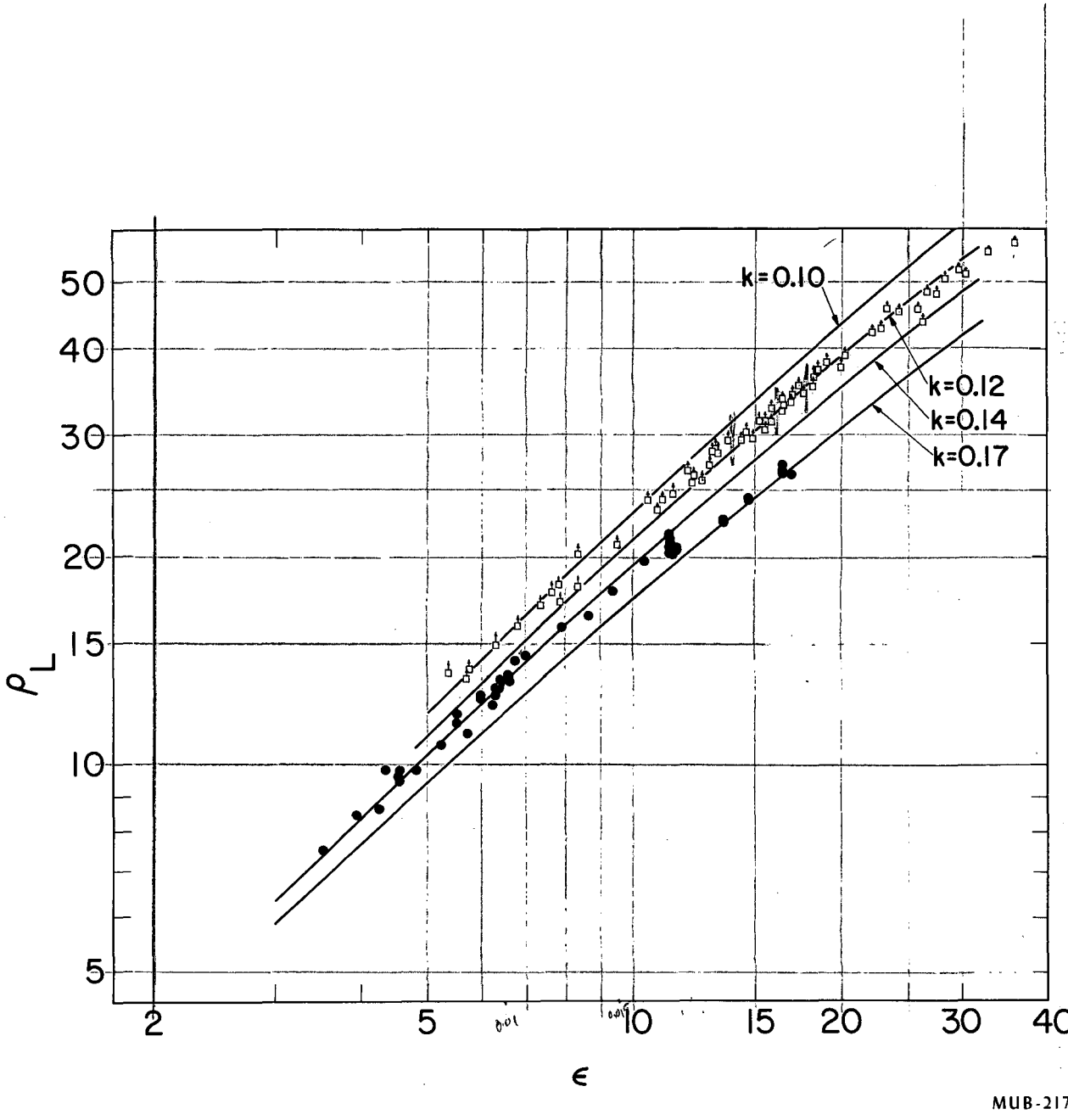

Fig. 3. Range-energy curves for Tb and Dy in H_2 and Al using the dimensionless variables ρ_L and ϵ. The tops of the arrows indicate the result of correction of projected range to "true range". Solid lines are theoretical, with the indicated values of the parameter k. ● Tb^{149}, $Dy^{149,150,151}$ stopped in hydrogen, k_{th} = 0.15; □ Tb^{149}, Dy^{149} stopped in aluminum, k_{th} = 0.11.

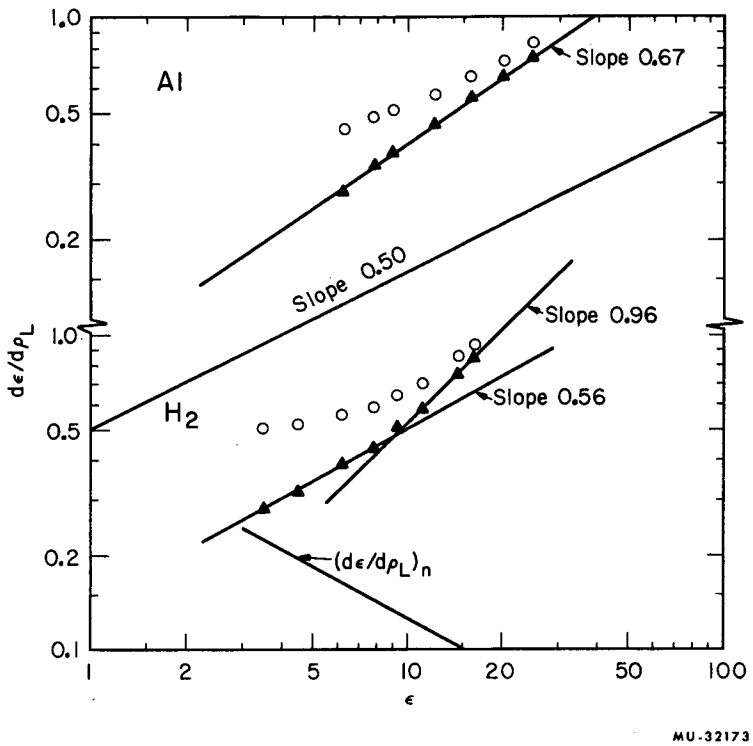

Fig. 4. Energy loss $(d\epsilon/d\rho_L)$ versus reduced energy ϵ for Dy stopped in H_2 and Al. Circles are from experimental data, curve labeled $(d\epsilon/d\rho_L)_n$ is theoretical nuclear stopping, and solid triangles represent electronic stopping obtained by difference.

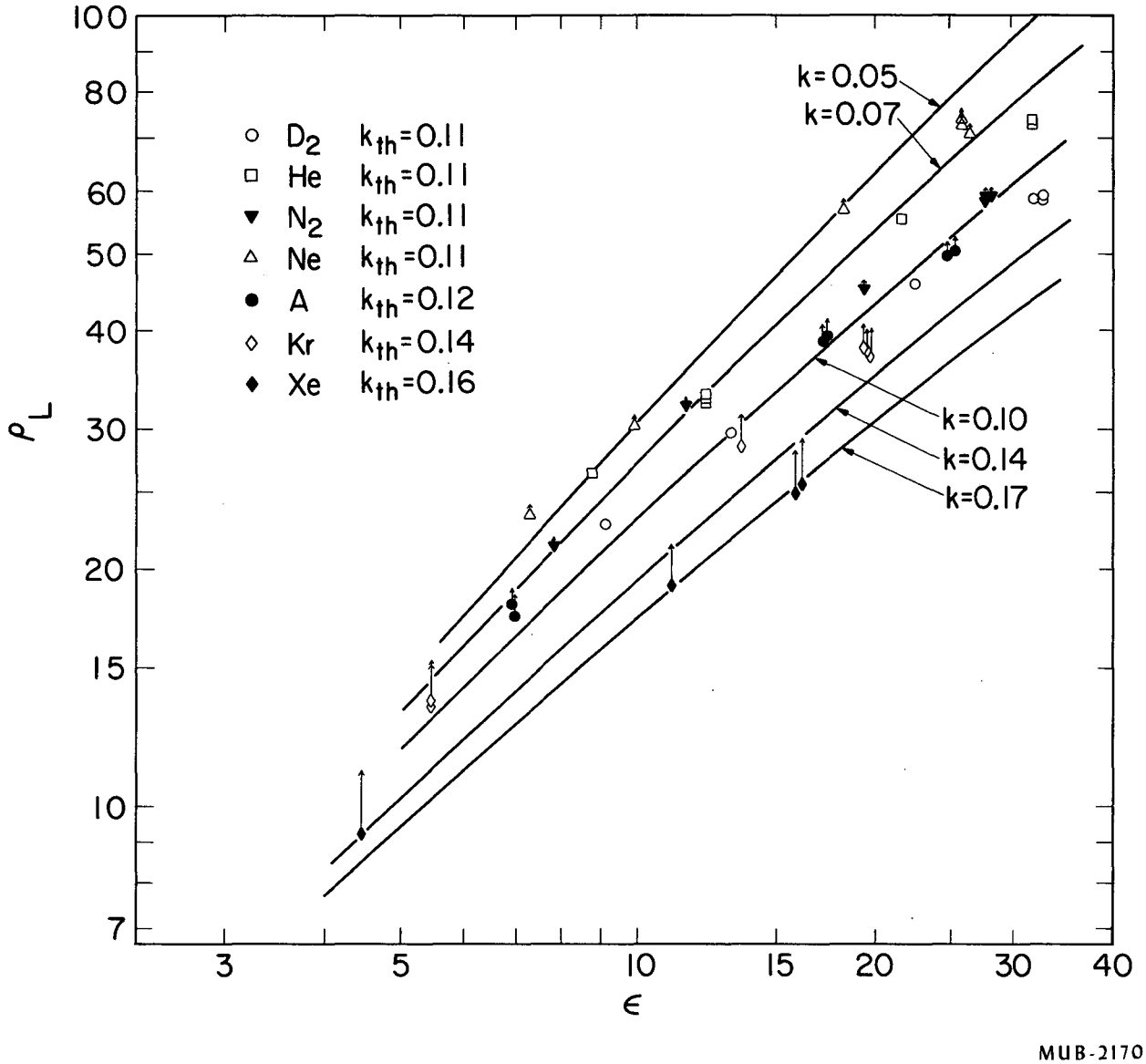

Fig. 5. Range-energy curves for Dy in various gases using the dimensionless variables ρ_L and ϵ .

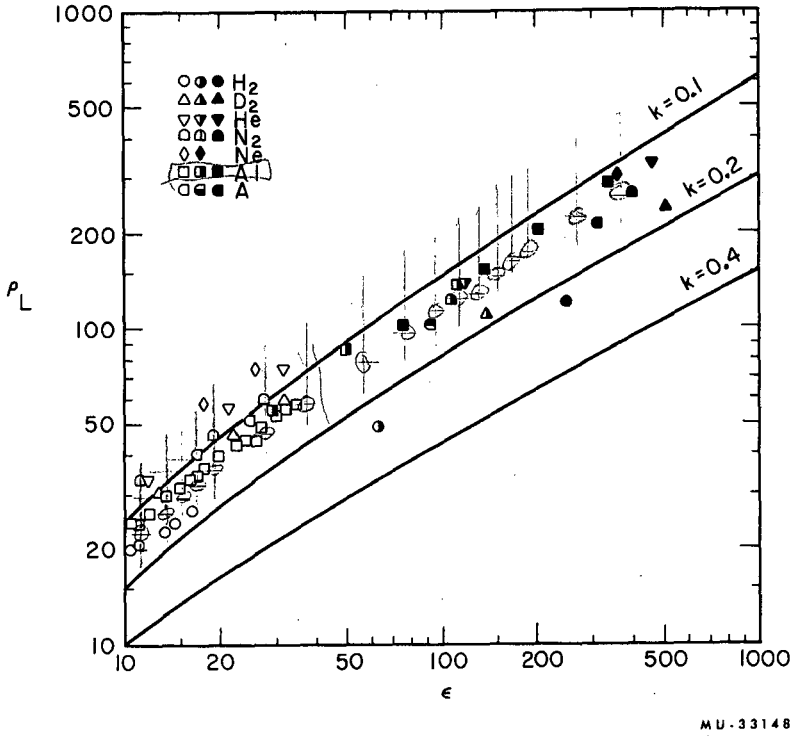

Fig. 6. Range-energy curves for Dy ions and fission fragments in gases and Al, using the dimensionless variables ϵ and ρ_L. Open symbols, Dy recoils; half shaded, heavy fission fragments; closed, light fission fragments.

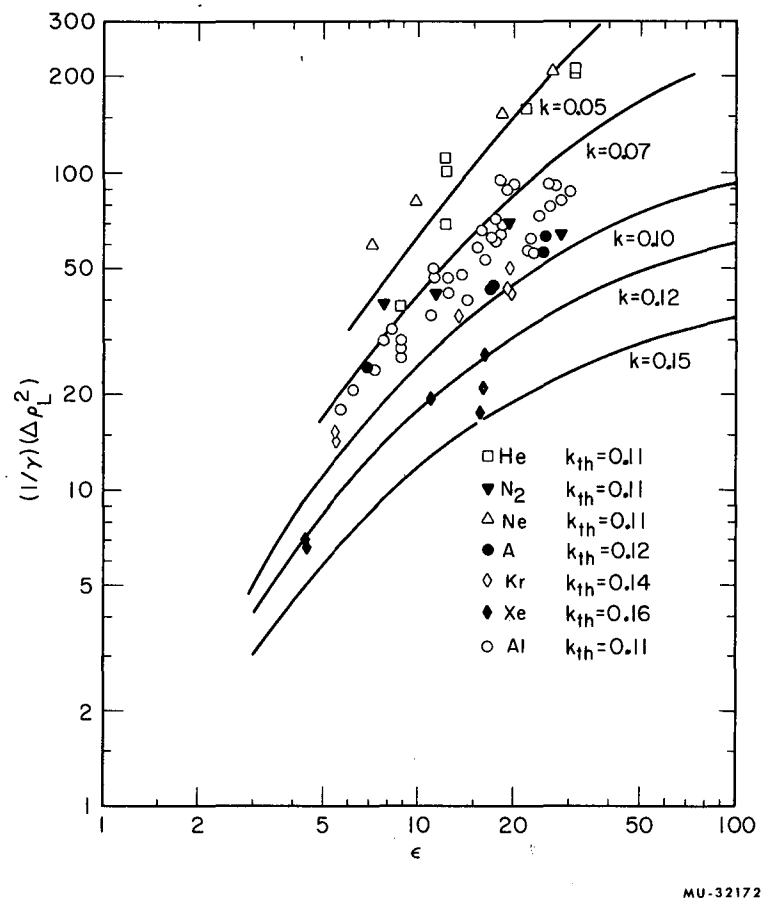

Fig. 7. Range straggling $\langle \Delta\rho_L{}^2 \rangle / \gamma$ $(\gamma = 4A_S\, A_R\, (A_S + A_R)^{-2}$; $\langle \Delta\rho_L{}^2 \rangle = \rho^2 \langle \rho_L{}^2 \rangle)$ as a function of reduced energy ϵ. The various stopping materials and theoretical values of k are indicated.

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