Energy loss of H^+ and He^+ in Al, Zn, and Au in the very low- to intermediate-energy range

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The energy loss of H^+ and He^+ ions in polycrystalline Al, Zn, and Au films has been determined by the transmission method in the energy range between 1 and 200 keV. The velocity dependence of the different projectile-target pairs has been analyzed, as well as the ratio of the energy losses of helium ions and protons in the different materials. An increase of this ratio toward very low velocities has been observed and possible explanations are explored. The results are compared with the existing theoretical models and semiempirical approximations, and observed differences are discussed. [S1050-2947(96)08309-6]

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I. INTRODUCTION

Energy losses of ions in solids have been extensively studied in the high-energy range, i.e., for projectiles faster than the Fermi velocity v_F of the target electrons. This is the range where perturbation models apply, such as in particular those based on Bethe-Bloch theory and effective-charge models. As one goes to lower velocities v, through the region of the energy-loss maximum and in the low-velocity range, experimental data show more and more dispersion, and most of the theoretical descriptions break down, even for the simplest case of protons. When dealing with He projectiles the uncertainties are even larger. In addition to increased theoretical difficulties, the experimental data are very scarce in the low-energy range. Another point in this respect is that there are no measurements made in similar experimental conditions covering the whole range from low to intermediate energies for helium ions, and therefore obviously not either for protons and helium ions simultaneously.

A useful parameter to compare the energy losses of these ions is the ratio R between the stopping of helium and hydrogen at the same velocity. The R values deduced from semiempirical formulas [1–3] are not in accordance with the predictions of newer low-energy calculations [4,5]. Another frequently used source of energy-loss data, the STOP program [6] gives — for the elements studied in this work — a target independent value for R, which shows a decreasing behavior with decreasing v as proposed in Ref. [7].

Some experimental works present proton and helium-ion energy losses measured under similar experimental conditions since the past decade [8–12], but none of them covers the interesting range of $v \ll v_F$. The R values from Refs. [10,12] show a target material dependence. Their values are very similar for Al, but different in the case of Au, especially at the lower velocity limit of their measurements. So uncertainties about the target dependence even at the velocities covered in these works still exist. On the other hand earlier [4,5] and more recent [13,14] theoretical developments, based on density functional (DF) and free-electron gas (FEG) theory, provide new models for the stopping of low-energy ions that give a good general description of nonlinear effects on the energy loss of slow ions. However, even in the case of protons, some discrepancies (of ~25%) subsist, which to the present have not been completely understood. The discrepancies refer both to the magnitude and to the velocity dependence of the energy loss. To investigate more completely the phenomenon of the energy loss of light ions we have performed a set of measurements in an extended energy range, using protons and helium ions under similar experimental conditions. Measurements have been made for energies ranging from 1 to 200 keV in elements with different free-electron densities: Al, Zn, and Au. The measurements for helium in Zn fill a complete lack of data in the whole covered energy range.

The measurements were performed by applying the transmission method, using very thin self-supporting targets, and collecting particles emerging within a small cone in the forward direction. Thus, the method provides forward electronic energy-loss values that can be easily compared with theory (especially theories not considering the angular or impact-parameter dependence of the phenomenon). The data are presented in terms of stopping cross sections fitted to the 200-keV proton values of the Andersen and Ziegler compilation [1] by assigning foil thicknesses based on these values.

II. EXPERIMENTS

The extended energy range from 1 to 200 keV was obtained by measurements performed with two ion accelerators of our laboratory: a low-energy accelerator operated in the range 1–10 keV, and a medium-energy accelerator operated from 10–200 keV. The measuring equipment has been described elsewhere [15,16]. A similar experimental setup for the transmission method was employed in both accelerators. The energy analysis was performed by electrostatic analyzers collecting the ions emerging from the target in the forward direction. The angular acceptance was $\pm 0.34°$ at lower energies and $\pm 0.05°$ at energies above 30 keV. The energy resolution was 2% at low energies, and 0.5% at energies above 10 keV. After this energy and angular selection, the ions were detected with open electron multipliers, followed by pulse electronics and multiscaler analyzers. The consistency of the measurements made with the different machines was checked by comparison of the energy-loss values at 10

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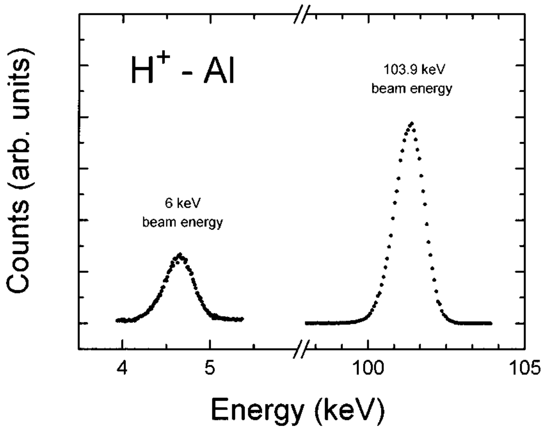

FIG. 1. Raw energy-loss spectra of transmitted protons in the low velocity and the intermediate velocity ranges.

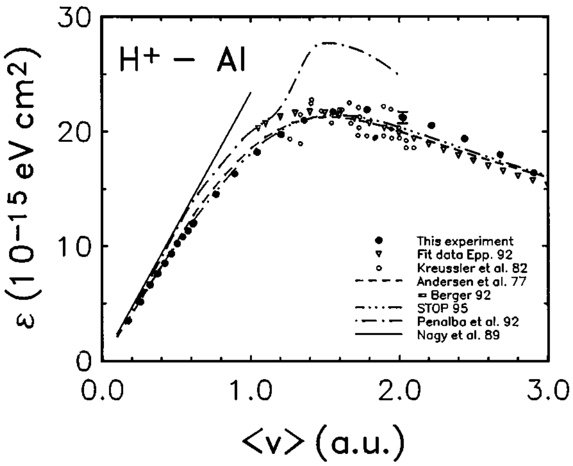

FIG. 2. Present data of energy loss (solid circles) in units of stopping cross sections, for protons in Al together with other experimental data and calculated values. The references corresponding to the abbreviations inserted in the figure are Epp. 92, Ref. [12]; Kreus 82 *et al.* 82, Ref. [10]; Andersen *et al.* 77, Ref. [1]; Berger 92, Ref. [3]; STOP 95, Ref. [6]; Peñalba *et al.* 92, Ref. [14]; Nagy *et al.* 89, Ref. [5].

keV, accessible to both systems. The matching between the values was in the range of $\pm 3\%$. The helium-ion and proton data were obtained under identical experimental conditions using the same foils for both projectiles. Each data point presented here is the mean value using two foils from the same batch. The self-supported targets were made by evaporation under clean vacuum conditions on a very smooth plastic substrate [17]. To overcome the condensation difficulties for Zn, a very small amount ($\sim 2\%$) of Ag was previously deposited on the substrate [18]. The effect of this deposit on the measured energy-loss values is well below the statistical uncertainties, as was estimated using tabulated values [1] and previous measurements made at this laboratory [16]. The foil thicknesses were determined by fitting the proton energy-loss measurements at 200 keV to the stopping cross section given by the Andersen and Ziegler tables [1]. The resulting thickness values were between 188 and 231 Å for Al, 194 and 205 Å for Zn, and 120 and 127 Å for Au. The foil roughness was evaluated by a beam technique [19] (which gives an upper limit) being at most 12%, 17%, and 10% of the mean foil thickness for Al, Zn, and Au, respectively. The Au foils were additionally analyzed with an atomic-force microscope, obtaining a value of 8% for the mean roughness, which is in good agreement with the upper limit of 10% obtained with the ion-beam method.

Foil thickening by beam bombardment [20] was held within negligible limits by using a very low ion current density of $\sim 10^{-9}$ A/cm^2, and irradiation times of the order of 2 min or less, per spectrum. In this way no change in foil characteristics could be detected during the time of measurements. The statistical errors of the present measurements are of the order of $\pm 2\%$.

Figure 1 shows two representative energy spectra of transmitted protons, for low (6 keV) and high (103.9) energies, without any smoothing. The cleanliness of the spectra allows an accurate determination of the energy loss of transmitted particles.

III. RESULTS

Figures 2–7 show the results of the energy losses of protons and helium ions in Al, Zn, and Au. The collection of data is also represented in a compact way in Table I. In order to collect all data in a single table, the measurements were fitted, and the results for round energy values are quoted, except for the first and last values in each column, which are the actually measured values. For comparison, Figs. 2–7 also show the classic semiempirical values of Andersen and Ziegler [1], Ziegler [2], Berger [3], and the 1995 version of the STOP program [6]. We notice that Ref. [3] does not include values corresponding to Zn, due to the lack of earlier data in the literature. The figures also include more recent theoretical predictions [5,13,14]. For projectile energies $E < 10$ keV, existing data for He from other sources [21,22] are included in the graphs. At higher energies we only include newer data [8–12]; in this case older measurements are indirectly taken

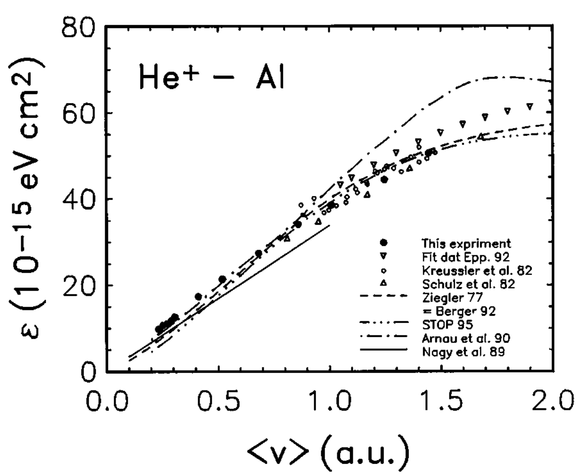

FIG. 3. Present data of energy loss (solid circles) in units of stopping cross sections, for helium ions in Al together with other experimental data and calculated values. The references corresponding to the abbreviations inserted in the figure are the same as in Fig. 2, and additionally: Ziegler 77, Ref. [2]; Schulz *et al.* 82, Ref. [11]; Arnau *et al.* 90, Ref. [13].

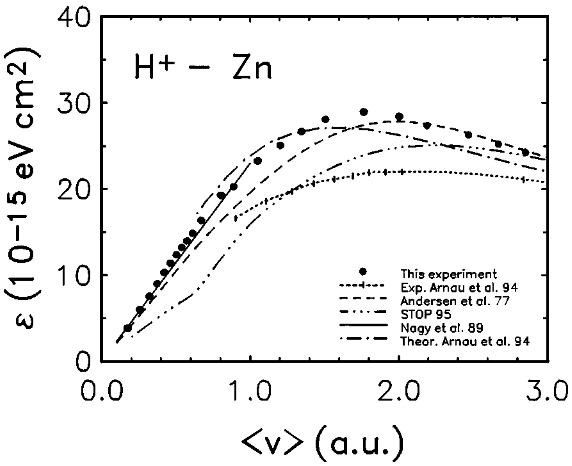

FIG. 4. Present data of energy loss (solid circles) in units of stopping cross sections, for protons in Zn together with other experimental data and calculated values. The meaning of the abbreviations inserted in the figure are Exp. Arnau *et al.* 94, experimental data in solid phase of Ref. [26]; Theor. Arnau *et al.* 94, theoretical values of the same reference, also for solid phase. The remaining abbreviations are the same as in the previous figures.

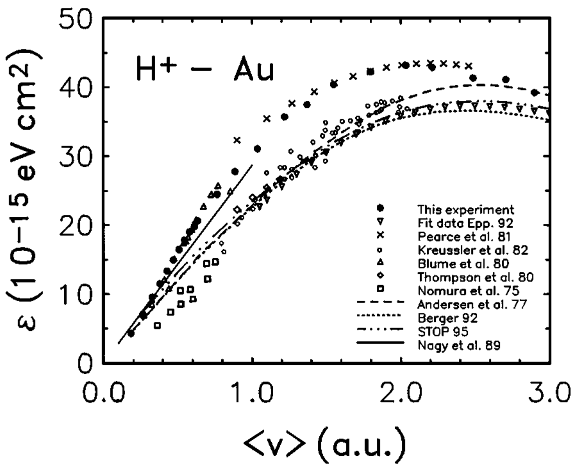

FIG. 6. Present data of energy loss (solid circles) in units of stopping cross sections, for protons in Au together with other experimental data and calculated values. The meaning of the abbreviations inserted in the figure are Pearce *et al.* 81, Ref. [9]; Blume *et al.* 80, Ref. [22]; Thompson *et al.* 80, Ref. [8]; Nomura *et al.* 75, Ref. [21]. The remaining abbreviations are the same as in the previous figures.

into account by the inclusion of the semiempirical curves of Refs. [1,2].

Our low-energy values for protons in Al and Au have been discussed in a previous paper [16]. The measurements of protons in Zn in the extended range have also been analyzed before [23]. The comparisons with other data and semiempirical values do not show a general trend. Each case has its particularities, as we will discuss below. The possible influence of impurities has been evaluated using the data of the STOP 95 program. The possible contaminants considered were H, N, O, and C. Assuming an upper bound of 10% for the impurity content, we estimated differences in the measured energy-loss values of ~2% in the worst cases.

The contribution of the elastic energy losses restricted to the forward direction has been calculated following the criterion of Ref. [24]. The largest contribution obtained is 4%, and corresponds to He on Zn at the lowest velocity (0.2 a.u.). For all other collision systems and energies the calculated contribution lies below the experimental errors. In the following, special features of each for the three elements are commented upon separately. As a consequence of the target thickness determinations, based on the 200-keV values from Andersen and Ziegler [1], the following comparisons with these tabulations refer to the energy dependencies rather than to the absolute values.

A. Aluminum

An interesting feature of the energy losses of both projectiles in this element, shown in Figs. 2 and 3, is the propor-

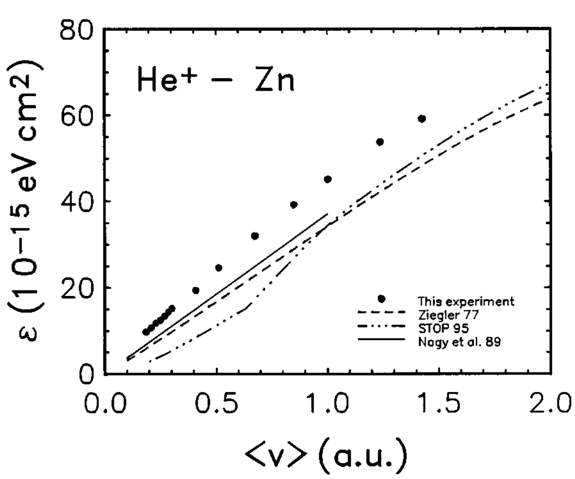

FIG. 5. Present data of energy loss (solid circles) in units of stopping cross sections, for helium ions in Zn together with the semiempirical values of Ziegler [2] (short-dashed line) and the STOP 95 program [6] (dashed–triple dotted line) and the calculations of Nagy *et al.* [5] (solid line).

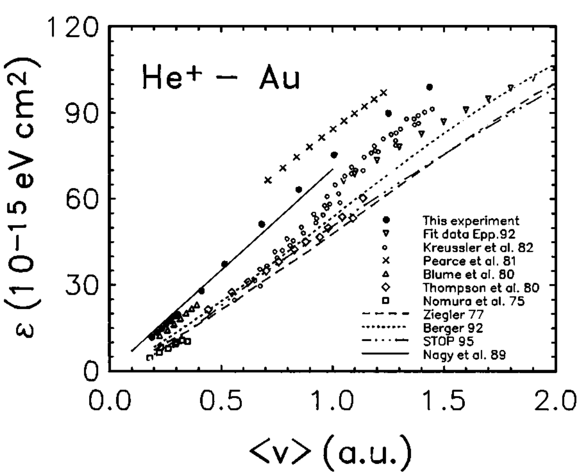

FIG. 7. Present data of energy loss (solid circles) in units of stopping cross sections, for helium ions in Au together with other experimental data and calculated values. The meaning of the abbreviations inserted in the figure are the same as in the previous figures.

TABLE I. Fitted experimental values of energy losses. The data do not contain extrapolated values. The cases of fractional energies correspond to experimental data and are the first or last values of the respective energy ranges.

Mean ion	Energy losses (10^{-15} eV cm^2)					
energy	H^+-Al	He^+-Al	H^+-Zn	He^+-Zn	H^+-Au	He^+-Au
0.75	3.54		3.70			
0.84					4.34	
1.00	4.07		4.40		4.77	
2.00	5.75		6.62		7.77	
3.00	7.22		8.20		10.35	
3.35				9.72		
3.56						11.80
4.00	8.08		9.63	10.40	12.40	12.45
5.00	9.16		10.75	11.42	14.10	14.27
5.34		9.78				
6.00	9.93	10.26	11.80	12.44	15.77	15.77
7.00	10.65	11.11	12.70	13.35	17.27	17.08
8.00	11.29	11.82	13.55	14.22	18.55	18.38
9.00	11.92	12.53	14.41	15.05	19.60	19.74
10.00	12.44	13.26	15.12	15.75	20.66	21.00
15.00	14.74	16.40	18.00	18.90	24.96	26.42
20.00	16.39	18.80	20.05	21.62	28.13	31.21
30.00	18.77	22.73	23.15	26.32	32.95	39.77
40.00	20.40	25.95	25.11	30.13	36.19	46.78
50.00	21.35	28.75	26.67	33.50	38.50	52.68
60.00	21.80	31.10	27.56	36.40	40.18	58.35
70.00	21.95	33.31	27.95	38.90	41.44	63.14
80.00	21.85	35.20	28.05	41.20	42.33	67.34
90.00	21.60	36.75	27.85	43.35	42.82	71.31
100.00	21.30	38.45	27.54	45.36	43.05	74.84
120.00	20.55	41.20	26.64	48.88	42.85	80.95
140.00	19.70	43.60	25.80	52.05	42.21	86.36
160.00	18.75	45.70	25.05	54.85	41.44	90.86
180.00	17.81	47.75	24.29	57.15	40.64	94.73
200.00	16.81	49.57	23.62	59.20	39.62	98.26
202.20			23.56			
204.20						99.03
206.60		50.54				
208.05					39.25	
210.00	16.35					

tionality with v at low velocities. We notice that in this range, where nonlinear models based on DF and FEG theory should apply, the calculations for H^+ of Refs. [5,14] predict slightly higher values than the present measurements (Fig. 2), whereas the opposite happens for helium ions (Fig. 3). The discrepancies are larger in the range of intermediate velocities. In particular, one cannot find experimental evidence for a structure in the curve as in the theoretical predictions near $v=1.2$ a.u. (Fig. 2). This may be an indication that either the capture and loss models, or the linear approximations used for intermediate velocities in Ref. [14], should be further analyzed.

In the case of this element the data at 200 keV from different tabulations [1,3,25] show a relatively small spread. References [1] and [3] give the same values, meanwhile the data of Paul *et al.* [25] lie ~3% lower. This limits the possible uncertainties that could arise from different normalizations. In the case of helium ions, we find that for $v<0.35$ a.u., the low-energy DF-FEG predictions of Refs. [5,13] lie ~15% below the data. In the region $0.5<v<0.8$ the agreement with the calculations of [13] is improved, whereas in the $v>1$ region the predicted values are clearly higher than our data. This last feature is similar to the behavior of the values calculated for protons using similar approximations (cf. Figs. 2 and 3). The comparison with the fits of Andersen and Ziegler [1] and Berger [3] for protons yields good agreement at lower energies up to the region immediately below the maximum. The fits for helium ions are steeper for $v \leqslant 1.5$ a.u. It should be noticed that for this element, the semiempirical curves of Ziegler [1,2] and those of Berger [3] are coincident for hydrogen as well as for helium projectiles.

B. Zinc

The results for this element are shown in Figs. 4 and 5. To our knowledge there exist no other data for helium ions in this range. A comparison of the proton results with other data [26] as well as the possible influence of the normalization procedure was discussed in detail in a previous paper [16]. The energy loss for both H and He projectiles follows a behavior approximately proportional to the velocity at low v, and the overall velocity dependence is smooth. We notice the significantly lower values predicted for He in the low-v range, by the DF-FEG calculations [5], as well as by the semiempirical formulas [2] (Fig. 5), in contrast with the much better agreement found for protons under the same conditions (Fig. 4). In particular the low-energy proton data show very good agreement with the DF-FEG calculations [5], and also a reasonable accordance with more recent calculations for intermediate and high energies [26]. Compared with the measurements in solids of Ref. [26], our data show a more pronounced maximum. In this case, for which no data were available when the well-known semiempirical fits by Andersen and Ziegler [1] were established, the predicted values for H^+ in Zn do not differ by more than 14% over the entire range, whereas the differences for He^+ are about twice this value. In the case of the STOP-95 values, the comparison is clearly worse; in particular, the break in the lines obtained from this program (both for protons and helium) can be considered to be spurious effects.

C. Gold

The results for H and He in Au are shown in Figs. 6 and 7. In the case of protons (Fig. 6), the proportionality with velocity at low v does not hold as in the cases of Al and Zn. This deviation from the theoretical predictions has been analyzed elsewhere [16]. The origin of this deviation was explained by a change with velocity of the effective number of target electrons participating in the energy-loss process. Due to the closeness in energy of the d electrons to the conduction s electrons, the former can be excited by protons with velocities larger than ~0.3 a.u. (threshold effect).

For H^+ the velocity dependence shows, as in the cases of Al and Zn, a smooth passage through the maximum. In this region we find rather large differences in absolute value as well as in the energy dependence with some other experimental data and with semiempirical values [1,3,6], and good agreement with the data obtained by Pearce and Hart [9]. The accordance with the low velocity data of Blume, Eckstein, and Verbeek [22] is excellent. In the case of this element the known data show a more pronounced spread even at 200 keV. So, when normalizing our values to a more recent tabulation [25], they would decrease by ~8%, falling somewhat nearer to the data of some other authors [3,8,10,12,21]. However, this would not affect the observed differences in the energy dependence, namely, a more pronounced maximum, and a shift towards lower energies. For helium ions, stopping values do not show any clear indication of deviations from velocity proportionality as obtained for protons. This may be attributed to differences in the scattering of electrons by slow protons and helium ions in an electron gas. Although the maximum energy transferable $T_{\max}$ from an ionic projectile to an electron is the same for both ions at the same velocity $T_{\max}=2mv(v+v_r)$, the scattering cross section for helium is larger [4] and shows a different angular dependence (larger angular dispersions of target electrons). An estimate of the threshold effect for helium in Au, made along the same lines as the one for protons [27] predicts indeed a smaller effect on the velocity dependence. As shown in Fig. 7, the present data are in good agreement (~8%) with the low-velocity measurements of Blume *et al.* [22]. One can also observe a rather large spread of the existing experimental data at intermediate energies, with differences of nearly a factor of 2 in certain cases (see Fig. 7). Finally, we find that the DF-FEG calculations of Nagy, Arnau, and Echenique [5] for He give a good fit to the present measurements, whereas the corresponding calculations for H projectiles are not in close agreement.

D. The energy-loss ratio *R*

The extended range of these measurements allows an investigation of the energy-loss ratio R, defined as

$$R=\left(\frac{dE}{dx}\right)_{\mathrm{He}}\bigg/\left(\frac{dE}{dx}\right)_{\mathrm{H}}, \qquad (1)$$

in the range of velocities given by $0.2\leqslant v\leqslant 1.5$ a.u. Since these measurements have been performed with the same foils for protons and helium projectiles, this ratio can be put in terms of the experimental energy losses as $R=\Delta E(He)/\Delta E(H)$.

Figures 8-11 depict our results. For comparison, R values derived from other existent data, [8–12,21,22] as well as the predictions arising from recent theories [5,13,14] are included. In the case of experimental data from other sources, we only considered those R values that can be obtained from an overlap of the velocity ranges for both H$^+$ and He$^+$ in the actual measurements (i.e., not including data based on extrapolations of either one of them). From this collection of data one can observe the following features: (1) There is a tendency of R to approach a nearly velocity-independent value for $0.3<v<1$. (2) For gold, and to a somewhat smaller extent also for Zn, there is an increase in the R values at lower velocities, $v<0.3$. (3) There is a moderate target material dependence. (4) The existing semiempirical fits and theoretical calculations show important discrepancies and fail to predict the behavior of the R values at low velocities.

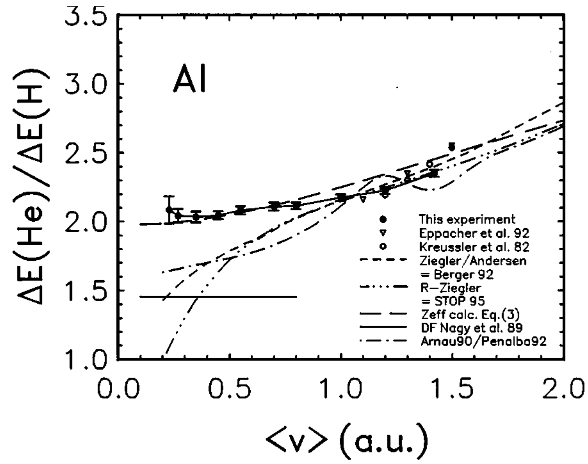

FIG. 8. Ratios of the energy losses of helium ions and protons in Al resulting from this experiments, and a semiempirical Z-effective approach for both ions, together with other values. The abbreviation Z_{eff} calc. Eq. (3) refers to the values arising from Eq. (3) considering the mean relative velocity v_r respect to the target electrons. R-Ziegler corresponds to Eq. (2), Ziegler/Andersen refers to the values resulting from Refs. [2,1], STOP 95 to those of Ref. [6] and Nagy *et al.* 89 to those of Ref. [5].

We interpret the above-mentioned velocity independence as a consequence of the proportionality with velocity of the energy losses of H$^+$ as well as He$^+$ in this range. Therefore, this is the velocity range where better comparison with theories based on free-electron gas models [4,5] may be expected.

The data for Au from different authors show an appreciable dispersion. However, the only existing data in the very low-energy range, by Blume *et al.* [22], yield very clearly the same enhancement in the R values with decreasing velocities (Fig. 10). As a possible explanation for these higher R values in Au at very low energies (enhancement effect) we have considered the so-called threshold effect observed for

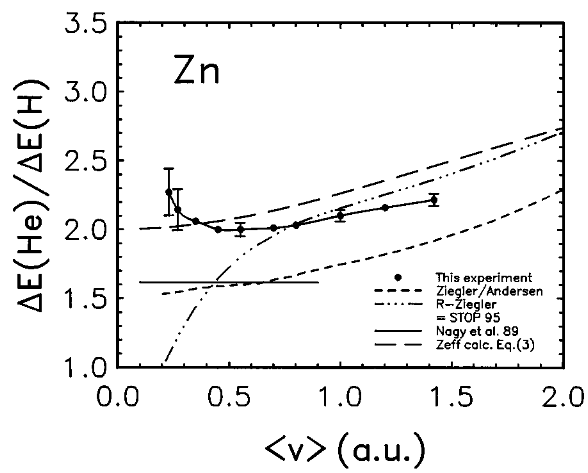

FIG. 9. Ratios of the energy losses of helium ions and protons in Zn resulting from this experiments, and a semiempirical Z-effective approach for both ions, together with other values. The abbreviations inserted in the figure have the same meaning as in Fig. 8.

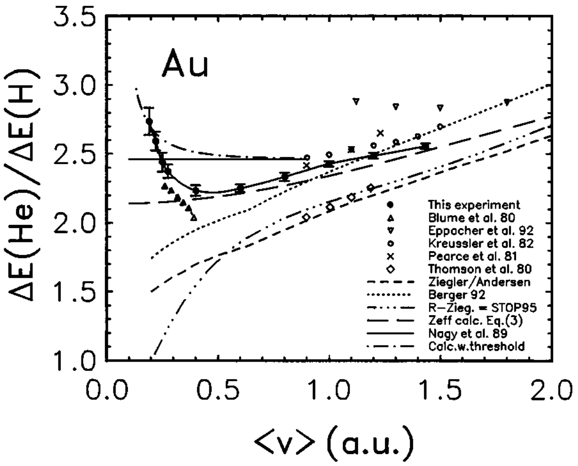

FIG. 10. Ratios of the energy losses of helium ions and protons in Au resulting from this experiments, a semiempirical Z-effective approach for both ions, and calculations including the threshold effect (see text), together with other values. The abbreviations inserted in the figure refer to values from the references specified in Figs. 6 and 9.

protons in Au [27]. Energy-loss calculations for helium using the phase shifts values obtained from the DF-FEG calculations [4] show a smaller threshold effect as expected from the arguments indicated before. Thus, the calculated energy-loss ratio R shows an increase at lower velocities, as illustrated in Fig. 10. The model gives only a fair indication of the enhancement in the R values, for velocities where it is experimentally observed, but it does not coincide in the absolute value of the overall effect. Therefore, we think a more definitive explanation of this effect should still be attempted.

The comparison with other experimental data shows a good agreement for Al [10,12]. The existing Au data show important spreads of ~35%, in the intermediate region explored by several other groups [8–10,12]. Our Au values agree well with those of Refs. [9,10]; as already mentioned, at low v, the R values derived from the data of Ref. [22] show a similar enhancement effect. The data of Ref. [21] allow the determination of only one value, which is 25% smaller than ours. Looking at the ratios derived from the semiempirical values of Refs. [1,2] we can observe that they start at 1 keV with a value of ~1.5 (for all these targets), and increase with projectile velocity. The target-independent universal curve for R proposed in Ref. [7]

$$R(v)=1-\exp\left\{-\sum_{i=0}^{5} a_i\left[\ln\left(\frac{m_{\mathrm{He}}v^2}{2}\right)\right]^i\right\} \qquad (2)$$

(with $a_0=0.2865$, $a_1=0.1266$, $a_2=-0.001429$, $a_3=0.02402$, $a_4=-0.01135$, and $a_5=0.001475$), increases even more steeply at low velocities. The predictions of Berger [3] for Al are coincident with those of Refs. [1,2]. At low energies the R values for Au in Ref. [3] are 13% higher than those for Al. That is to say, the semiempirical predictions for low energies do not show the dependencies with ion velocities nor with target material observed in this experiment.

In order to test another approach for the stopping power problem, we evaluated the R values following the usual

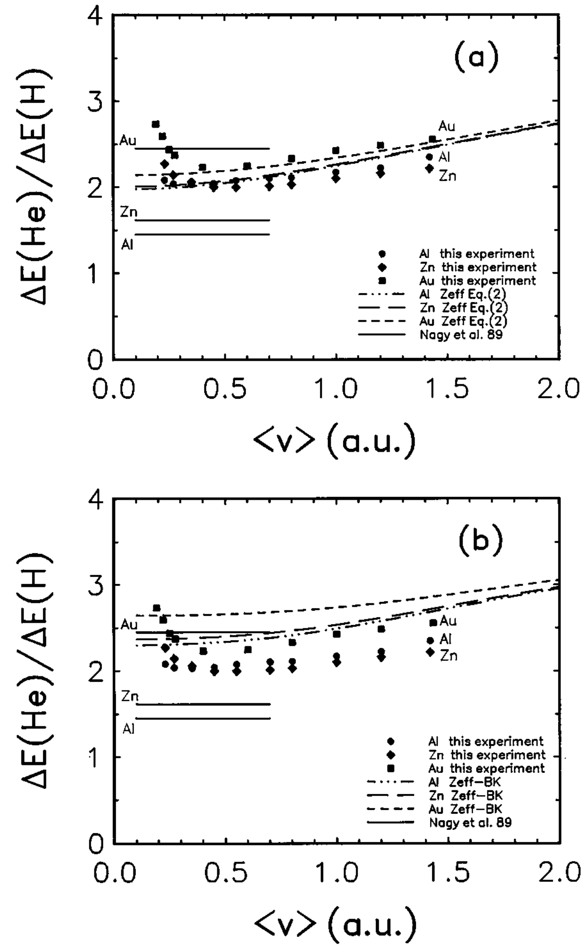

FIG. 11. Ratios of the energy losses of helium ions and protons in Al, Zn, and Au resulting from this experiments (solid symbols) and from two different Z-effective approaches: (a) semiempirical Z_{eff} values obtained using Eq. (3) with v_r, and (b) results from the Brandt-Kitagawa model (Z_{eff}-BK), applied to protons and helium. The solid lines show the values arising from the DF-FEG calculations (Ref. [5]).

effective-charge concept [7,28–32]. In this case one gets a relation $R=(2\gamma_{\mathrm{He}}/\gamma_{\mathrm{H}})$, where the γ's are the fractional effective charges ($\gamma=Z_{\mathrm{eff}}/Z_1$) for He and H at the same velocity. To calculate γ_{He} and γ_{H} we applied the models derived by Brandt and collaborators [29–32].

The case of H deserves special consideration. In an earlier publication [30] an effective charge $Z_p(v)$ for the proton was proposed, which gave a best fit to the stopping power data in a large number of materials; however, in later publications [31,32] the proton charge was fixed to 1, using the argument that a screened proton would not bind an electron while moving through the solid [29]. This argument was in a way contradicted by recent calculations [14], based on DF theory for a ''jellium'' model of the solid, where the proton is regarded as binding up to two electrons (although one should note that the DF calculations are strictly applicable to a stationary proton only). We will not discuss here the validity of these models; however, based on the present data for the stopping ratios between He and H, we may now rule out the previous assumption [29] that the proton remains bare at velocities below the stopping maximum. If that were the case, the R values would become much smaller than those shown in Figs. 8–10 for $v \ll 1$ a.u., following the drop of the helium effective charge.

Based on this evidence, we use here in a tentative way a description for the proton charge $Z_p(v)$ similar to that proposed by Yarlagadda *et al.* [30], and calculate the effective-charge fractions γ_{He} and γ_{H} from the Brandt-Kitagawa (BK) model [32]. Moreover, to calculate the effective charges we have used the mean relative velocity v_r of the ions with respect to the target electrons, following the extension proposed by Brandt and collaborators [11,30–32] for the case where the ion moves with velocities similar to, or smaller than, the Fermi velocity of the electrons.

Another representation of the effective-charge approach, which has been applied with very good results in a large number of cases (mostly for heavier ions and larger velocities) is the simplest effective-charge description according to the ''Betz-approximation'' [28]:

$$Z_{\mathrm{eff}}(v) = Z_1\left[1-\exp\left(-\frac{\alpha v}{Z_1^{2/3}}\right)\right], \tag{3}$$

which is based on scaling properties derived from the statistical-atom picture [7,28], for an ion with velocity v and atomic number Z_1 (with a fitting parameter $\alpha = 0.95$). Following Brandt's arguments, [31–33] we will replace in this expression the ion velocity v by the relative velocity v_r. We show in Fig. 11(b) the calculated R values using for H and He the effective charges Z_{BK} emerging from the BK model [32] (where the ionization degree for the proton is obtained from Ref. [28], and the relative velocity v_r is used), and in Fig. 11(a) we show similar comparisons using the simplest effective-charge approximation of Eq. (3) (also with $v \to v_r$). These approaches, although quite phenomenological at this point, give a fairly good representation of the experimental stopping ratios R for lower v values ($v \leqslant 1.3$ a.u.), particularly the simplest Z_{eff} model, Eq. (3), with $v \to v_r$. A rather light target-material dependence results, quite similar to the experimental one. The stopping ratios R obtained from this model approach constant values in the very low-velocity limit. The density functional calculations for a free-electron gas [5], which give a velocity-proportional energy loss, predict of course velocity-independent ratios R, although they yield a too-strong material dependence.

IV. CONCLUSIONS

Energy losses of protons and hydrogen ions transmitted in the forward direction through thin Al, Zn, and Au foils have been measured in an extended energy range from 1 to 200 keV. In the case of protons this covers both regions of main interest: the low-velocity region and the region around the stopping power maximum. The data for helium ions, obtained under identical experimental conditions, allow the investigation of the energy-loss ratio R for these projectiles in the region around $v = 1$, and the unexplored low-velocity range down to $v = 0.2$ a.u. In distinction with the behavior of the proposed universal curve for R [7], which predicts a continuous decrease of the R values towards low velocities, especially at the lowest velocities, we find a tendency to become constant for $v \leqslant 0.6$ a.u. Moreover, below $v = 0.3$ a.u. an unexpected increase of R was observed in the cases of Au and Zn. Some arguments have been explored in order to explain this new effect, but it does not seem possible at this moment to get a conclusive explanation of the behavior for the three elements investigated.

The existing theoretical models to describe the phenomenon of energy loss of light ions in metals, in the low- and intermediate-energy ranges, are still unable to describe in a satisfactory way the data obtained for protons and helium ions in Al, Zn, and Au, under equal experimental conditions over an extended low-energy range. It seems that further theoretical efforts should be made to provide a description of the differences between the stopping coefficients of ions in these metals. The semiempirical energy-loss tabulations and fitting formulas derived from higher-energy data do not agree with the present measurements for lower energies, except for protons in Al. For practical purposes, the extension to low velocities of the semiempirical approximation for the effective charge, Eq.(3), using Brandt's ansatz, $v \to v_r$, provide reasonable estimations of the energy-loss ratios in Al, Zn, and Au, down to velocities of 0.3 a.u.

In summary, the present energy-loss data, from simultaneous measurements with hydrogen and helium ions, provide new tests for theoretical models and semiempirical predictions in the range of low and intermediate velocities.

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