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Estimation of the Stopping Powers of the ${}^{A}Z = {}^{300}120$ Ion in Al and UO_2

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The electronic and nuclear stopping powers of a superheavy ion with $Z = 120$ and $A = 300$ in Al and UO_2 were estimated in the energy range of 0.01–0.20 MeV/u. The electronic and nuclear stopping powers of ions with $6 \leq Z \leq 92$ obtained from Stopping and Range of Ions in Matter (SRIM) were used to estimate the corresponding stopping powers of the superheavy ions. The results were compared with those deduced from Northcliffe and Schilling's stopping-power tables. In the lower energy region the contribution of the nuclear stopping powers is significant in both media, while it is not negligible even in the higher energy region.

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I. INTRODUCTION

The synthesis of superheavy elements has presented the challenge of finding their optimal reaction channels and corresponding excitation functions. Typical reaction cross sections of the superheavy elements with $Z \geq 112$ are in the pb range and their productions are affected by the excitation energy [1]. They go through various media and experience energy losses in the process. In the study of the excitation function of superheavy elements, their energy losses have to be known along with their masses, which can be taken from one of the mass tables [2–4].

The electronic stopping-power and range tables for ions with $1 \leq Z \leq 103$ at 38 energies ranging from 0.0125 to 12 MeV/u in 24 media have been reported by Northcliffe and Schilling [5]. Hubert *et al.* [6] reported electronic stopping-power and range tables for 2.5–500 MeV/u ions with $2 \leq Z \leq 103$ in 36 solid materials. However, nuclear stopping powers were not listed in both tables. Electronic and nuclear stopping powers of ions with $Z \leq 92$ in various media can be obtained from Stopping and Range of Ions in Matter (SRIM) [7], but the stopping powers of charged particles with $Z \geq 93$ are not available. Experimental data and the expected values of stopping powers for heavy ions with $Z \geq 104$ are scarce, but the stopping powers of ^{289}Fl ($Z = 114$) in Mylar were reported [8].

In the 0.5–10 MeV/u energy range, significant discrepancies have been reported between the experimental stopping powers and those of Northcliffe and Schilling's tables [5], particularly for light stopping media and heavy projectiles [9–11]. The discrepancy of 4.9 MeV/u ^{84}Kr in Al reaches 30% [9]. For energies higher than 2.5 MeV/u, the tables of Hubert *et al.* [6] give the best predictions of stopping powers. Northcliffe and Schilling's

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tables underestimate the stopping powers, especially for light stopping media [11]. This trend was observed in the study of the energy loss of 8.46 MeV/u ^{136}Xe passing through three media, such as Havar foil, nitrogen gas, and a ^{248}Cm target substrate [12]. Besides, nuclear stopping powers of heavier ions appear to be significant.

Superheavy elements have been produced using heavy actinides [13–19], namely U, Np, Pu, Am, Cm, Bk, and Cf. An attempt to search for a superheavy element with $Z = 120$ has been tried using the reaction of ^{238}U with ^{64}Ni projectiles [20]. Reaction products typically go through a target, He of a recoil separator, and isobutane in a multiwired avalanche counter with a Mylar window [21]. In the previous work [22], electronic and nuclear stopping powers of the superheavy ion with $Z = 120$ and $A = 300$ at 26 energies ranging from 0.0177 to 0.141 MeV/u in UF_4, He, Mylar, and butane have been estimated. In this work its stopping powers in Al and UO_2 are estimated at 35 energies ranging from 0.01 to 0.20 MeV/u.

II. ENERGY LOSS OF SUPERHEAVY IONS

The energy-loss processes for superheavy ions are fundamentally similar to those for heavy ions. As an ion becomes heavier, its energy-loss process is dominated by the charge variation due to electron capture and loss at low velocities and elastic collisions with the screened nuclei of the medium. The resulting stopping power has two contributions: an electronic one arising from energy transfer of the ion to the electrons of the medium and a nuclear one due to energy transfer to screened nuclei of the medium. The nuclear contribution for eight ions ranging from H to Fm in Al has been reported [5], where it is noticeable below ~ 0.02, ~ 0.1, ~ 0.3, and ~ 0.5 MeV/u for H, Cl, I, and Fm, respectively.

Superheavy ions have been produced by either cold or hot fusion. Their typical kinetic energies were in the vicinity of 0.1 MeV/u from cold fusion, and still below 0.3 MeV/u even in hot fusion. The stopping-power tables of Hubert *et al.* [6] would not be applicable to heavy ions in this lower energy region. SRIM data [7] are available only for ions up to $Z = 92$, while Northcliffe and Schilling's tables [5] provide only electronic stopping powers up to $Z = 103$.

The stopping power of the heavy ion in a given stopping medium, $-(dE/dx)_{ion}$, depends on its effective charge γZ where γ^2 and Z are the effective charge parameter and the atomic number of the ion, respectively. The effective charge of the heavy ion can be calculated by the scaling law [5]

$$(\gamma_{ion} Z_{ion})^2 = (dE/dx)_{ion} / [(dE/dx)_{ref} / (\gamma_{ref} Z_{ref})^2], \tag{1}$$

where $-(dE/dx)_{ref}$ is the stopping power of a reference ion of the same velocity and $\gamma = 1$ means that the ion is fully stripped. The effective charge parameter of the ion at velocity v is described by the following relation [5, 23]

$$\gamma = 1 - e^{-v/v_{TF}}, \tag{2}$$

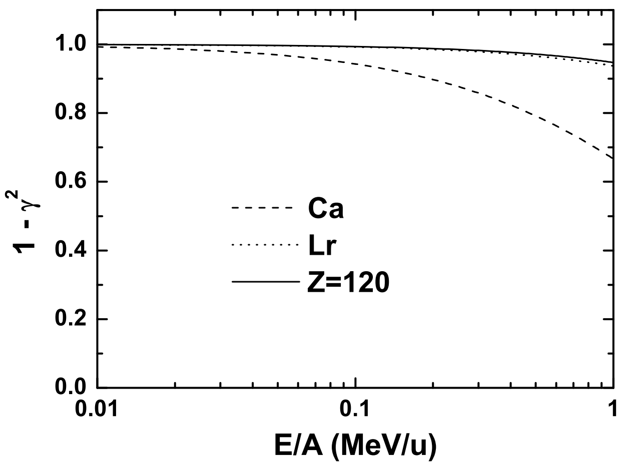

FIG. 1: Variation of effective charge parameter with ion velocity for Ca, Lr, and $Z = 120$ ions.

where $v_{TF} = Z^{2/3}v_o$ is the Thomas-Fermi velocity and v_o is the Bohr velocity (2.188×10^6 m/s). This equation can be written as follows:

$$\gamma = 1 - \exp[-B_1(E/A)^{1/2}Z^{-2/3}], \tag{3}$$

where B_1 is 6.3498, E is the ion energy (MeV), and A is the ion mass (u). The relation between the ion velocity and the effective charge parameter is shown for Ca, Lr, and $Z = 120$ ions in Fig. 1. Fig. 1 shows that the effective charge parameters of the Lr and $Z = 120$ ions behave similarly. This implies that the stopping power of the $Z = 120$ ion in the same medium could be extrapolated from the data listed for heavy ions.

The more explicit effective charge parameterization given by Hubert *et al.* [6] is rearranged as the relation [22]

$$\gamma = 1 - (C_1 + 1.658 \exp[-0.05170Z]) \exp[-C_2(E/A)^{C_3}Z^{C_4}], \tag{4}$$

where C_1, C_2, C_3, and C_4 are parameters depending on the atomic number of the stopping medium. This manifests that the effective charge is affected by the atomic number, energy, and mass of the ion and the atomic number of the medium. Consequently, the electronic and nuclear stopping powers of ions at a given value of E/A in the same medium will be Z-dependent.

II-1. Stopping powers of superheavy ion with $Z = 120$ and $A = 300$ in Al

Electronic and nuclear stopping powers of 77 ions ranging from C to U in Al at 35 energies have been obtained from SRIM [7], where Bragg's Rule has been applied to target compounds such as Mylar and UO_2. Their atomic numbers are 6, 10, 14, 18, 20, 21, 22, 23, ..., 91, and 92. Their 35 energies range from 0.01 to 0.20 MeV/u.

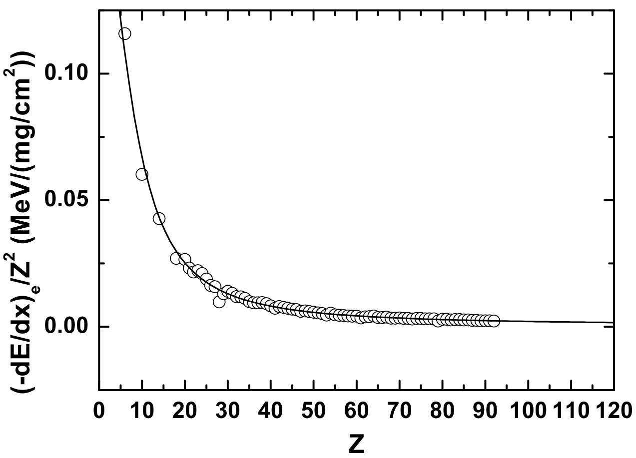

FIG. 2: Z-dependence of the electronic stopping powers of ions in Al at 0.10 MeV/u. Open circles are obtained from SRIM [7], and the curve refers to a fit with Eq. (6).

Electronic stopping powers of ions in all media including Mylar at each energy were fitted directly with the following function [22]:

$$-dE/dx = a_1 + a_2 Z + a_3 Z^2 + a_4/(1 + \exp[a_5(Z - a_6)]). \tag{5}$$

In this work the electronic stopping powers of ions divided by Z^2 are fitted by another function,

$$(-dE/dx)/Z^2 = a_1 + a_2 \exp[-a_3/Z^{2/3}]). \tag{6}$$

The electronic stopping powers of ions with $6 \le Z \le 92$ at 0.10 MeV/u are shown in Fig. 2. They vary smoothly with Z except for the Ni ion. The curve in Fig. 2 is a fit obtained with Eq. (6). The corresponding residuals are shown in Fig. 3.

The solid curve in Fig. 2 shows that the adopted fit works better than one obtained with Eq. (5), enough to extrapolate the electronic stopping power of the ^{300}120 ion in Al, since Fig. 3 shows that the fitted stopping powers agree well with those of most ions within less than 10% variation except for five ions: Ne with 11%, Ni with 48%, I with 14%, Pm with 19%, and Au with 25% variation. These large variations are due to the fact that they have much lower electronic stopping powers than their neighboring ions do. Similar results have been obtained for the other energies.

Electronic stopping powers of the ^{300}120 ion have been deduced at 35 energies ranging from 0.01 to 0.20 MeV/u and are shown in Fig. 4. The electronic stopping powers of ^{238}U ions at 0.0125, 0.10, and 0.20 MeV/u deduced from SRIM [7] are 9.6, 19.1, and 27.5 MeV/(mg/cm^2), respectively, while their corresponding values in Northcliffe and Schilling's tables [5] are 6.0, 21.0, and 32.0 MeV/(mg/cm^2). Their discrepancy is close to 60% at

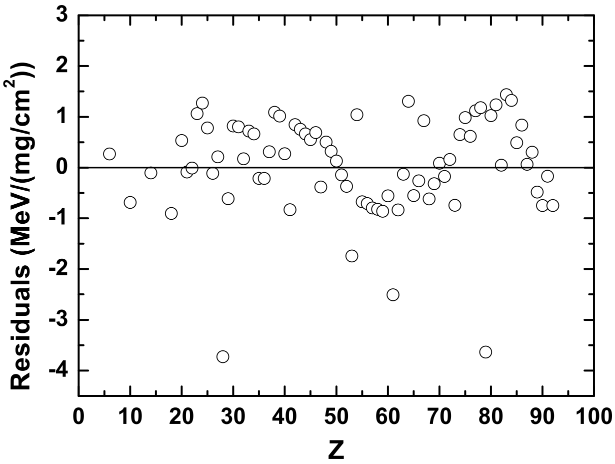

FIG. 3: Residuals of the electronic stopping powers of ions in Al in Fig. 2.

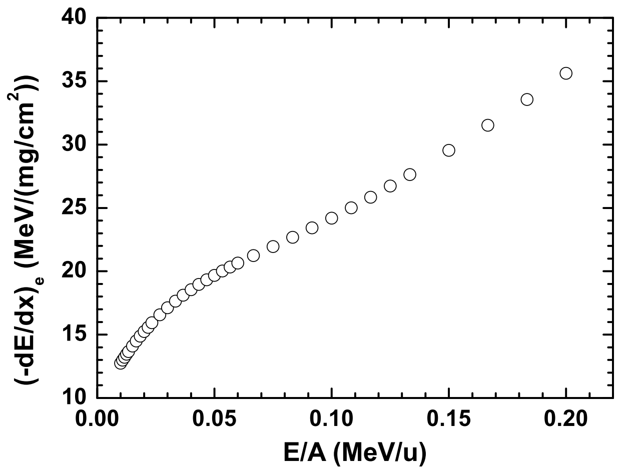

FIG. 4: Electronic stopping powers of the ^{300}120 ion in Al at 35 energies ranging from 0.01 to 0.20 MeV/u.

0.0125 MeV/u and decreases to 10% at 0.1 MeV/u. The electronic stopping powers of Lr ions estimated at 0.10 and 0.20 MeV/u are 21.5 and 32.0 MeV/(mg/cm^2), respectively, while their corresponding values in Northcliffe and Schilling's tables are 22.3 and 34.0 MeV/(mg/cm^2). Their discrepancies in this energy region are less than 10%.

The nuclear stopping powers of the corresponding ions are readily extrapolated to $Z = 120$ with a fifth-order polynomial fit [22]. The result at 0.10 MeV/u is shown in Fig. 5

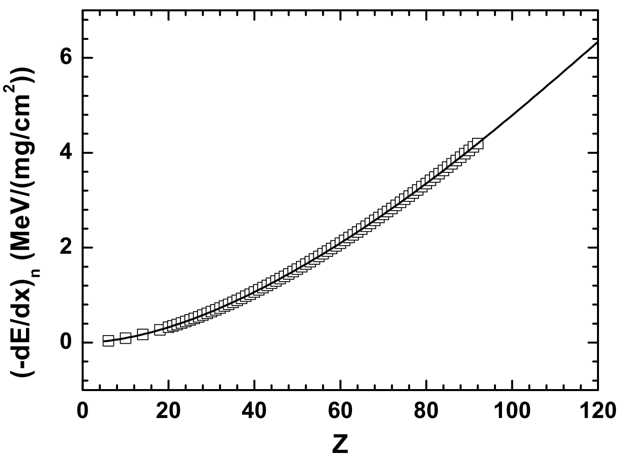

FIG. 5: Z-dependence of nuclear stopping powers of ions in Al at 0.10 MeV/u. Open squares are obtained from SRIM [7] and a curve refers to a fifth-order polynomial fit.

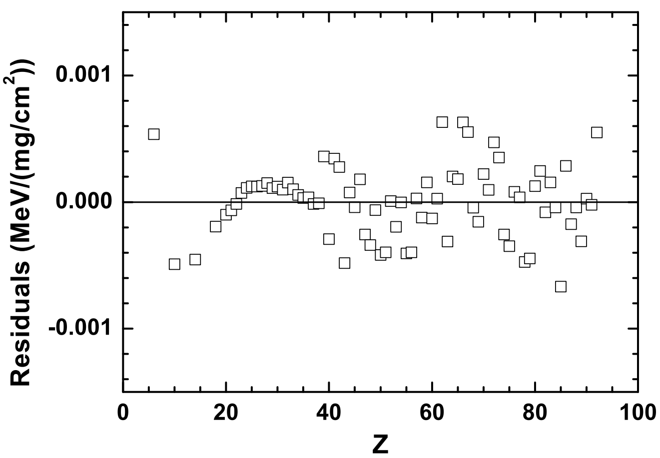

FIG. 6: Residuals of nuclear stopping powers of ions in Al in Fig. 5.

and the corresponding residuals in Fig. 6. The curve shows that the fit agrees with the data within far below 1% variation, except for the C ion with 1.4%. Similar results have been obtained for the other energies. Consequently, the nuclear stopping powers have been extrapolated at 35 energies like the electronic stopping powers, as shown in Fig. 7.

The electronic and nuclear stopping powers of the 0.10 MeV/u ^{300}120 ion were deduced to be 24.2 and 6.3 MeV/(mg/cm^2), respectively. This implies that the nuclear

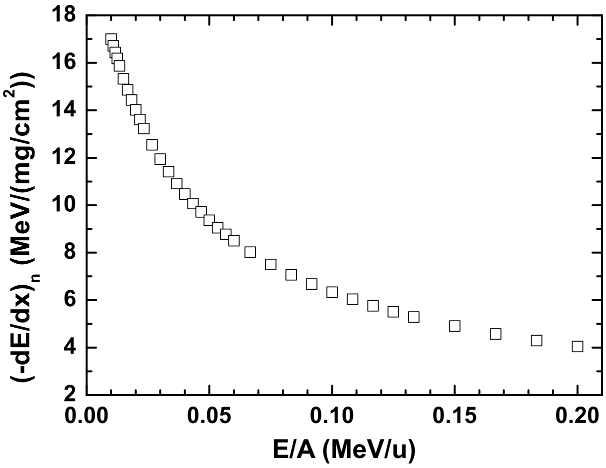

FIG. 7: Nuclear stopping powers of the ^{300}120 ion in Al at the same energies as in Fig. 4.

TABLE I: Electronic and nuclear stopping powers of ^{289}Fl in Mylar

E	$(-dE/dx)_e^a$	$(-dE/dx)_e^b$	$(-dE/dx)_n$	Experiment [8]
MeV			MeV/(mg/cm^2)	
24.7 ± 4.0	33.6 ± 3.0	30.2 ± 2.7	8.3 ± 1.2	34.9 ± 15.4

[a] The stopping power was deduced by Eq. 5.
[b] The stopping power was deduced by Eq. 6.

contribution is $\sim$ 21%. At 0.01 MeV/u its electronic and nuclear stopping powers were estimated to be 12.7 and 17.0 MeV/(mg/cm^2), respectively. The nuclear contribution is $\sim$ 57%. The total stopping powers of the ^{300}120 ion with ^{238}U ion in Al are shown in Fig. 8. They tend to decrease slowly until 0.04 MeV/u, and then increase smoothly as the energy increases, while the stopping powers of the ^{238}U ion decrease until 0.017 MeV/u, then increase and will reach a peak around $\sim$ 0.8 MeV/u, as shown in SRIM [7]. This trend at the lower energy region was also shown in the stopping powers of heavy ions [5]. This is simply due to significant nuclear stopping powers below 0.05 MeV/u.

Electronic stopping powers of ^{289}Fl ($Z = 114$) in Mylar deduced with Eqs. 5 and 6 along with their corresponding nuclear stopping powers are listed in Table I with the experimental value [8]. The electronic stopping power deduced by Eq. 6 is lower by $\sim$ 11% than that obtained by Eq. 5. Both values agree with the experimental one. This implies that the estimation can be applicable to $Z = 114$.

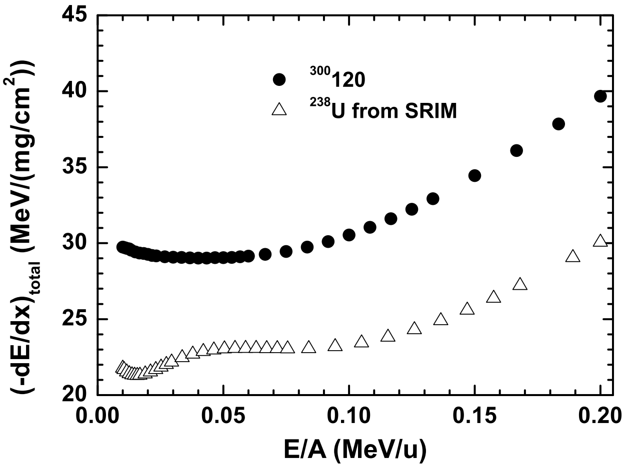

FIG. 8: Total stopping powers of the ^{300}120 and ^{238}U ions in Al at the same energies as in Fig. 4.

II-2. Stopping powers of the superheavy ion with $Z = 120$ and $A = 300$ in UO_2

The electronic and nuclear stopping powers of 77 ions ranging from C to U in UO_2 at 35 energies have been obtained from SRIM [7], where Bragg's Rule has been applied to the target compound. The electronic and nuclear stopping powers of the ^{300}120 ion in UO_2 have been estimated similarly as stated in the previous section. The electronic stopping powers of ions with $6 \leq Z \leq 92$ at 0.10 MeV/u are fitted with Eq. 6, as shown in Fig. 9. The corresponding residuals are shown in Fig. 10.

Fig. 10 shows that the fitted stopping powers agree well with those of most ions within less than 10% variation except for four ions: Ni with 48%, I with 14%, Pm with 19%, and Au with 25% variation, similarly as observed in Al. Similar results have been obtained for the other energies.

Electronic stopping powers of ^{300}120 ion have been estimated in the same energy range and are shown in Fig. 11. The electronic stopping powers of the ^{238}U ions at 0.10 and 0.20 MeV/u deduced from SRIM [7] are 7.2 and 12.4 MeV/(mg/cm^2), respectively, while their corresponding values in Northcliffe and Schilling's tables [5] are 6.3 and 11.6 MeV/(mg/cm^2). Their discrepancies are within a 14% variation at both energies. The electronic stopping power of the Lr ion estimated at 0.10 and 0.20 MeV/u is 8.1 and 14.4 MeV/(mg/cm^2), respectively, while their corresponding values in Northcliffe and Schilling's tables are 6.7 and 12.4 MeV/(mg/cm^2). Their discrepancies are within a 21% variation.

The nuclear stopping powers of the corresponding ions are readily extrapolated to $Z = 120$ with a fifth-order polynomial fit. The result at 0.10 MeV/u is shown in Fig. 12 and the corresponding residuals in Fig. 13. The curve shows that the fit agrees with the data within far below 0.01% variation. Similar results have been obtained for the other energies. Consequently, the nuclear stopping powers have been extrapolated at 35 energies

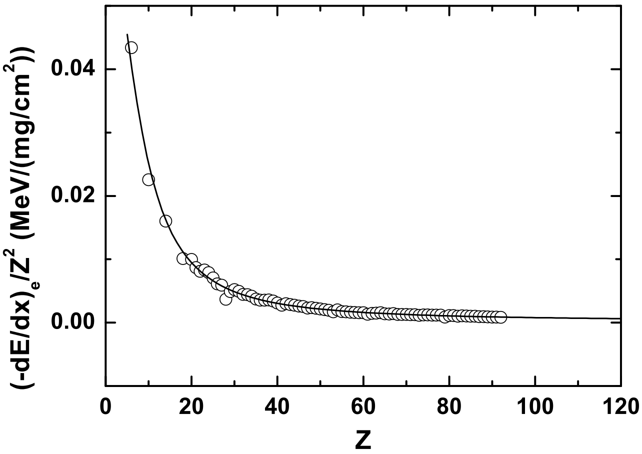

FIG. 9: Z-dependence of the electronic stopping powers of ions in UO_2 at 0.10 MeV/u, as shown in Fig. 2.

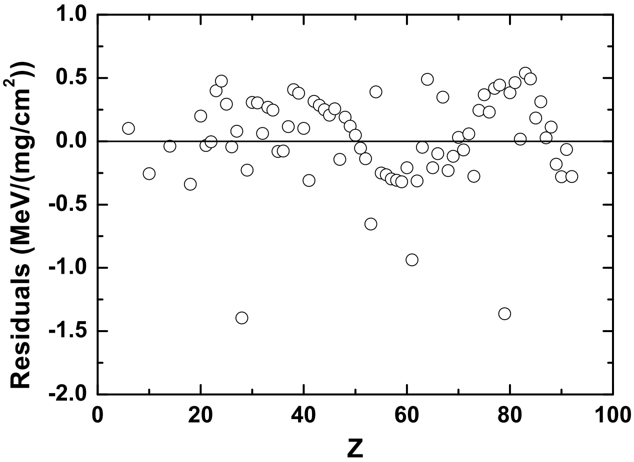

FIG. 10: Residuals of the electronic stopping powers of ions in UO_2 in Fig. 9.

like the electronic stopping powers, as shown in Fig. 14.

The electronic and nuclear stopping powers of the 0.10 MeV/u $^{300}120$ ion were deduced to be 9.1 and 3.8 MeV/(mg/cm^2), respectively. This implies that the nuclear contribution is $\sim$ 29%. Its corresponding stopping powers at 0.01 MeV/u were 2.9 and 8.7 MeV/(mg/cm^2), respectively. The nuclear contribution is nearly 75%. The total stopping powers at 35 energies ranging from 0.01 to 0.20 MeV/u are shown in Fig. 15, where they

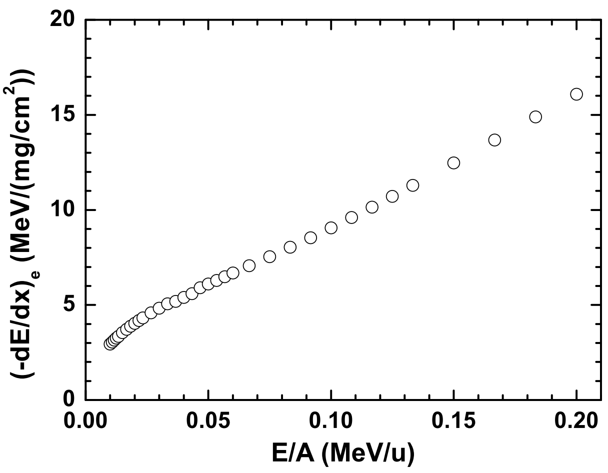

FIG. 11: Electronic stopping powers of the $^{300}120$ ion in UO_2 at the same energies as in Fig. 4.

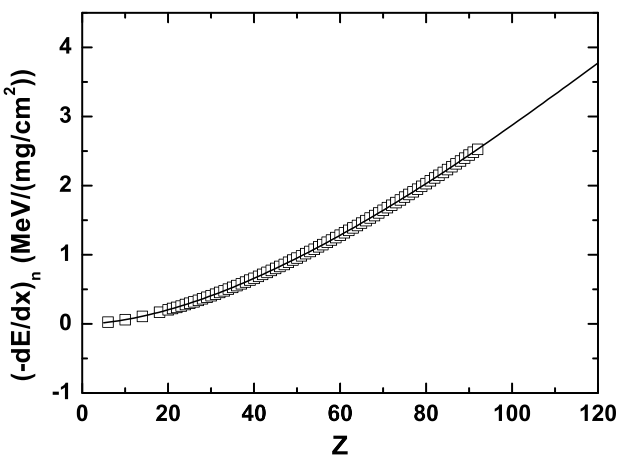

FIG. 12: Z-dependence of nuclear stopping powers of ions in UO_2 at 0.10 MeV/u, as shown in Fig. 5.

decrease slightly until near 0.04 MeV/u, and then they start to increase as the energy increases, while the stopping powers of the ^{238}U ion decrease until 0.017 MeV/u, just as in Al, and then increase.

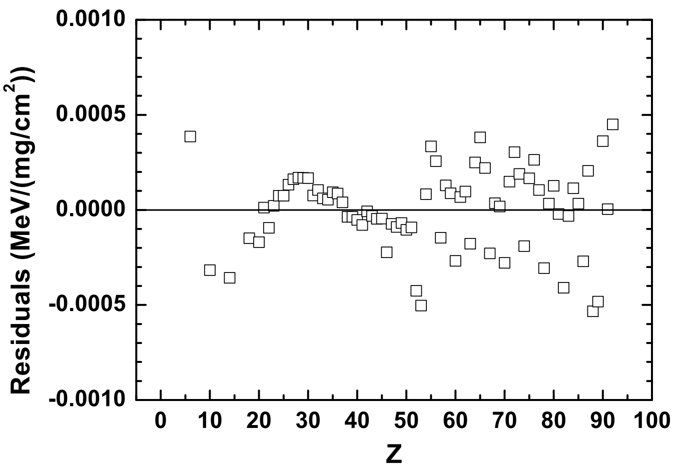

FIG. 13: Residuals of the nuclear stopping powers of ions in UO_2 in Fig. 12.

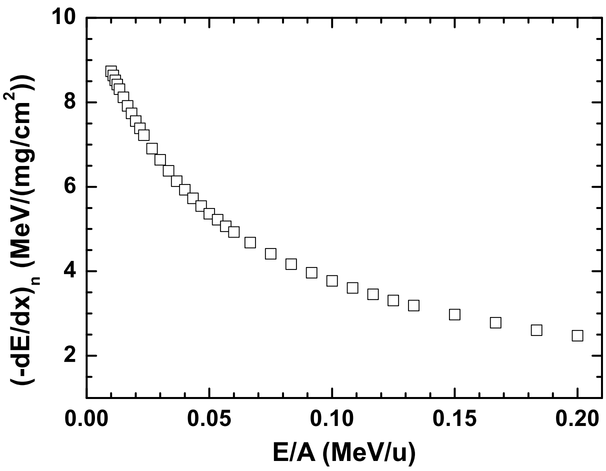

FIG. 14: Nuclear stopping powers of the $^{300}120$ ion in UO_2 at the same energies as in Fig. 4.

III. SUMMARY

Electronic and nuclear stopping powers of the superheavy ion with $Z = 120$ and $A = 300$ in Al and UO_2 in the energy region ranging from 0.01 to 0.20 MeV/u have been extrapolated using the data obtained from SRIM. Electronic stopping power of the ^{289}Fl ion in Mylar deduced using Eq. 6 agrees well with the experimental value. This estimation would be applicable to $Z = 120$. Electronic stopping powers of the Lr ion in two media at

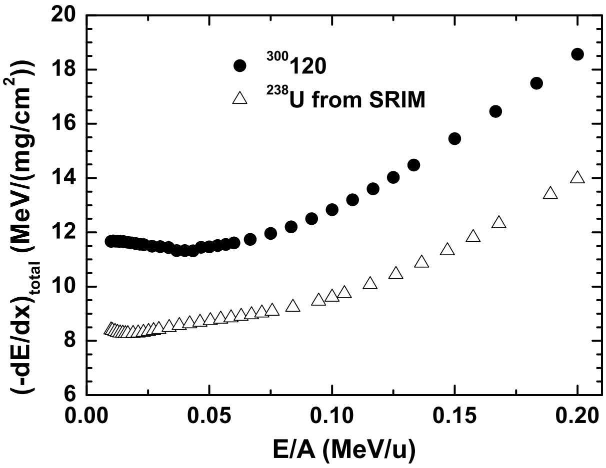

FIG. 15: Total stopping powers of the ^{300}120 and ^{238}U ions in UO_2 at the same energies as in Fig. 4.

0.10 and 0.20 MeV/u were compared with those deduced from Northcliffe and Schilling's tables. Their discrepancies in Al are less than 10%, while those in UO_2 are within a 21% variation. The contribution of the nuclear stopping powers is significant in this energy region. The nuclear contribution in Al varies from ~ 10 to $\sim 57\%$, while in UO_2 it varies from ~ 13 to $\sim 75\%$.

Estimation on the stopping powers of superheavy ions is very challenging because there are little experimental data. Using the data from SRIM, electronic and nuclear stopping powers of superheavy ions could be extrapolated to $Z \geq 120$ with the Z-dependent functions with three parameters for the electronic stopping powers and with a fifth-order polynomial for the nuclear counterparts. The results are to be scrutinized in detail and compared with the available experimental data for heavy ions with $Z > 92$ in the future.

Acknowledgments

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