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Stopping powers and ranges for the heaviest atoms

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ABSTRACT

Slowing down and stopping of the heaviest atoms, products of the fusion–evaporation nuclear reactions, during their passage through the Dubna gas-filled recoil separator has been studied using TRIM simulations. The study is important for experiments on the synthesis of super-heavy elements (SHEs) with atomic numbers around $Z_P = 114$ produced with accelerated heavy ion (HI) beams and extracted with a separator for their detection. The average Mylar stopping power (SP) values obtained with the simulations for HIs with $82 \leqslant Z_P \leqslant 92$ reveal almost the same magnitudes, allowing extrapolation to the region of $Z_P > 92$. Similar extrapolation of the ranges in an He + Ar gas mixture leads to rather small values for the heaviest atoms ($Z_P \geqslant 102$) as compared to the range for U. The extrapolated values have large uncertainties and should be verified with different approaches. Available SP data obtained for HIs with $18 \leqslant Z_P \leqslant 92$ at energies $E < 20$ MeV/u have been analysed within various semi-empirical approaches. The analysis has shown that existing parameterizations give Mylar SP values for $Z_P \geqslant 82$ that are very different from each other at energies of interest (around 0.1 MeV/u). We propose to use a general approach based on the HI effective charge parameterization obtained with available SP data for HIs and the hydrogen SP and effective charge corresponding to the same velocity and stopping medium as those for HIs. In this manner, the SPs of the gases H_2, He, C_4H_{10}, and Ar as well as those of the solids Mylar, C, Al, and Ti have been obtained for any atoms with $Z_P \geqslant 18$ (including the heaviest ones) at their reduced velocities $0.03 \leqslant V_{red} \leqslant 5.0$. The SP values derived in such a way seem to be more reliable compared to the existing semi-empirical calculations and can be used in the conditioning of experiments on the synthesis of SHEs.

1. Introduction

Experiments on the synthesis of super-heavy elements (SHEs) with accelerated heavy ion (HI) beams and studies of their physical and chemical properties are challenges in modern nuclear physics and nuclear chemistry research [1]. These experiments may need to take place over a period of several months in order to detect only a few atoms of SHEs produced in the fusion–evaporation reactions at the pb level of cross-sections. Such conditions are mainly determined by the available intensities of HI beams ($\sim 5 \cdot 10^{12}\ s^{-1}$) and the overall efficiency of recoil separators used for the extraction of SHEs, which corresponds to several tens of percent. The severe conditions of these experiments require definite notions on the transmission and stopping of the atoms of SHEs, particularly their energy losses inside the units of a device. In the Dubna Gas-Filled Recoil Separator (DGFRS) [2], fusion–evaporation reaction products or evaporation residues (ERs) knocked out from the target by the momentum of an HI beam particle lose their initial kinetic energy due to the slowdown inside the target material, the bulk volume of rare hydrogen gas, a thin Mylar foil, and the layer of pentane steam of a proportional chamber (time-of-flight system). Finally, they are implanted into a front Si-detector array (SDA). Such a scheme of the ER transmission corresponds to 'physical' experiments related to the synthesis and study of the radioactive properties of SHEs [1]. In 'chemical' experiments, atoms of SHEs pass through a thicker Mylar foil and are stopped inside a collecting reaction chamber (CRC) filled with a carrier gas (Ar or a mixture of Ar and He). The thermalized atoms of SHEs are transported through a long capillary to a low background area where a device for the study of their chemical properties [3] is located. Fig. 1 shows a sketch of the ERs' passage through the different media followed by their stopping inside one of the two terminal units of DGFRS.

One can trace the energy losses and scattering of ERs inside the units of the DGFRS using SRIM calculations or Monte Carlo TRIM simulations [4]. First, one should take into account the initial spreads in the kinetic energy and emission angle of ERs, which are caused by the evaporation of neutrons from a compound

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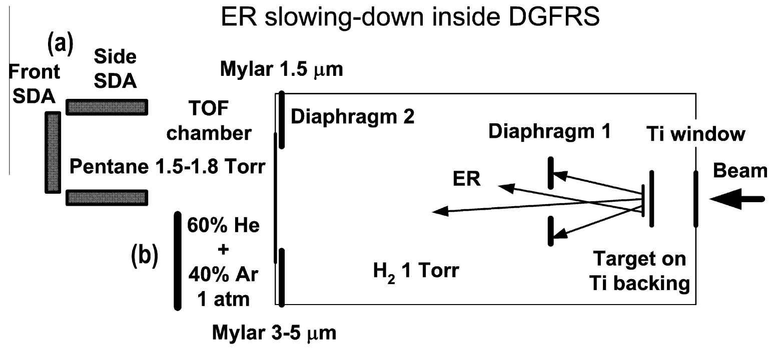

Fig. 1. A sketch of the slowdown of evaporation residues (ERs) inside the media of the Dubna Gas-Filled Recoil Separator [2]. ERs are stopped by a front Si-Detector Array (SDA) after their passage through H_2 filling the separator volume, a thin Mylar window, and a layer of pentane steam of a proportional chamber in 'physical' experiments (a), or by a gas mixture of He and Ar after their passage through a thicker Mylar window in 'chemical' experiments (b).

nucleus formed in the complete fusion of the projectile and target nuclei with subsequent scattering and energy losses of ERs inside the target [5]. In 'chemical' experiments the range distribution of the heaviest atoms inside the gas of the CRC, which depends on the Mylar foil thickness and the gas pressure, determines the volume (depth) of the chamber. It should be as small as possible in order to transport ERs further to a 'chemical' device as fast as possible [3]. The problem is that SRIM/TRIM cannot calculate the energy losses and ranges for HIs heavier than U ($Z_P = 92$), whereas the region of SHEs is in the vicinity of $Z_P = 114$. Note that at present, besides the DGFRS, a number of gas-filled recoil separators installed at HI beam lines deal with the study of SHEs in various laboratories of the world (see, for example, references in [1]).

This work was motivated by the need to have reliable estimates of the energy losses and ranges for the heaviest atoms with $Z_P > 92$ at their energies corresponding to the present-day and nearest future experiments for the study of SHEs. First, we report the results of our Monte Carlo TRIM simulations applied to the transmission of the heaviest atoms of ERs through the DGFRS followed by their stopping inside the gas of the CRC (see Fig. 1b). Then we compare the available Mylar SP data for HIs with the SRIM/TRIM calculations/simulations and a few other semi-empirical calculations. Slowdown in Mylar is the most crucial factor for the further estimates of the ER ranges in gases for the experiments with the DGFRS. Finally we propose a new semi-empirical parameterization for the SP estimates based on measured SP data and the notion on the effective charge of a swift HI inside matter.

2. TRIM simulations

The effective transmission of the heaviest atoms of ERs formed in a complete-fusion reaction followed by the evaporation of neutrons is mainly determined by the target thickness and the entrance geometry of a recoil separator. As shown in the experiment and by means of the simulation [5], the maximum transmission efficiency of the heaviest ERs knocked out from the target by the ^{48}Ca projectile corresponds to a target thickness of about 0.5 mg/cm^2. Obviously, this value corresponds to the definite entrance geometry of the DGFRS, which is determined by the size of the first diaphragm and its remoteness from the target (see Fig. 1). At this thickness, a non-negligible portion of the HI projectile energy is absorbed by the target layer. This absorption corresponds to the definite part of the excitation function describing the energy dependence of the production cross-section for a nucleus under investigation. That is the case for the experimental study of the chemical properties of the SHE produced in the ^{243}Am(^{48}Ca, 3n) reaction leading to the ^{288}115 nucleus [6]. The calculated excitation functions for this reaction do not perfectly reproduce the measured cross-section values. The last could be approximated with a *LogNormal* function of the projectile energy. This approximation makes it possible to obtain the probability of the ER's appearance inside the target as a function of its thickness and thus to set the initial conditions for ERs traversing the target layer [5].

The initial ER angular and energy distributions caused by the evaporation of neutrons, multiple scattering on target atoms, and energy losses inside the target material (0.567 mg/cm^2 of AmO_2) were obtained as described in [5] for ^{288}115 produced in the ^{243}Am(^{48}Ca, 3n) reaction at the ^{48}Ca input energy of 246 MeV. These distributions obtained with the TRIM simulations for the ^{288}Pb and ^{288}U ERs are shown in Fig. 2 (denoted as 'from target'). They were used for further simulations of the ER passage through the different stopping media of the DGFRS, taking into account its specific geometry. Since U is the heaviest HI with which TRIM deals, extrapolations of the energy losses and ranges for ERs with $82 \leqslant Z_P \leqslant 92$ to the heavier ones ($Z_P > 92$) are the subject of our study. In Fig. 2 we show the distributions for the ^{288}Pb and ^{288}U ERs, which are extracted from the initial ones ('from target') and correspond to those obtained behind the first diaphragm D1 (an oval inscribed into the rectangle of 24×36 mm^2) placed at a distance of 280 mm from the target. The next cutting-out of the initial distributions occurs (see Figs. 1b and 2) behind the inner space of the DGFRS (354 cm in length) filled with H_2 at 1 torr, which is bound by the second diaphragm D2 (the rectangle of 30×100 mm^2). Finally, we obtain the energy and angular distributions for ERs leaving the Mylar foil (see Fig. 2), which were used to obtain the final range distributions for the ^{288}Pb to ^{288}U ERs in the He (60%) plus Ar (40%) mixture at 1 atm of gas pressure. In our simulations, we applied a scaling formula to the scattering angles of the ^{288}Pb to ^{288}U ERs to convert these angles to those for ^{288}115, as was proposed in [5]. As we can see in Fig. 2, the angular distributions obtained for Pb and U are indistinguishable from each other with this correction. For the energy distributions of the ^{288}Pb to ^{288}U ERs, no corrections converting their energy losses to those for $Z_P = 115$ have been made (the same atomic mass number $A_P = 288$ in the simulations implies the nominal correspondence of the distributions to the same ER velocity). The difference in the energy distributions becomes visible for ERs leaving the Mylar foil and reaches a significant amount for the ^{288}Pb and ^{288}U range distributions.

Fig. 3 shows the statistics of our simulations for the range distributions of the ^{288}Pb to ^{288}U ERs in the He–Ar gas mixture after their transmission through the DGFRS. The values of the average range R_{av} and of the standard deviation σ_R converted to the relative range straggling $\rho = \sigma_R/R_{av}$ are shown in the figure. As we can see, the R_{av} values can be linearly fitted for the estimates of the extrapolated values at $Z_P > 92$. Similar simulations for the HI