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# Electronic stopping power of Ti, V and Cr ions in Ge and Au at 150–500 keV/u energies

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ABSTRACT

In this paper new experimental data are presented for the stopping power of Ti, V and Cr ions in Ge and Au, in the 150–500 keV/u energy range. The heavy ions at low energies are produced from the elastic scattering between particles of an energetic primary beam ($^{28}$Si and $^{16}$O) directed onto the primary foil of interest (Ti, V or Cr). Measurements were performed using the transmission method. New experimental data points for the stopping power of Ti in Au were compared with previous measurement. The agreement between these two datasets indicates the consistence of the experimental technique. Our experimental data were also compared to some selected theoretical and semi-empirical methods: i) the Unitary Convolution Approximation, ii) the Binary theory, iii) the SRIM code and iv) the Northcliffe & Schilling tables. The experimental data for Ge foil deviate from the theoretical curves possibly due to the effect of band gap structure of the material in the electronic stopping power. For the systems measured here, we observe that the Binary theory exhibits an overall good agreement. The velocity-proportional dependence of the electronic stopping power in the measured energy range is also discussed.

## 1. Introduction

There is a growing interest in understanding the details of the complex atomic collisions in the low energy regime. Reliable predictions of the energy loss of charged particles in solids are important for many applied fields [1]. Surface analysis using the Secondary-ion mass spectrometry (SIMS) requires an accurate knowledge of the energy loss of the ion during the sputtering process and depth distributions for heavy-ion implantations are relevant in semiconductor production [2,3]. In nuclear structure experiments, the Doppler shift attenuation method is employed to determine the lifetime of nuclear states [4,5]. In this technique, the stopping power curve is exploited to establish the picosecond timescale for the excited state lifetime measurement. Often these techniques deal with heavy ions slowing down in matter at energies below the Bragg peak.

During the passage of ions through matter, inelastic collisions between the projectile and target atoms are the dominant mechanism of energy loss over a wide range of velocity (i.e. $v \gg v_0$, where $v_0$ is the Bohr velocity). This mechanism is referred as the electronic stopping power (ESP) since it leads to excitations and ionizations of one or both partner atoms. At energies well above the Bragg peak ($\geqslant$1 MeV/u), the projectile particles move into matter entirely stripped out of their electrons. The ESP in this energy range can be described with few parameters [6,7] and scalings that produce numerical predictions with relatively good accuracy [8,9].

At energies around and below the Bragg peak, the projectile is partially screened by its electrons and, consequently, effects of the dynamical charge state come into play. In the low energy regime, with velocities below 1 atomic unit (a.u.) (equivalent to $\leq$ 25 keV/u), the ESP competes with elastic collisions between the projectile and the target atom. Such a collision depends on the interatomic potential and, within the Born–Oppenheimer approximation, the nuclear stopping is entirely independent of the electronic one. The Lindhard, Scharff and Schiott (LSS) theory was a landmark approach. The LSS theory considers the interaction of a charged particle with a free-electron gas and makes use of the local density approximation to obtain the ESP [10]. According to the LSS theory, the ESP exhibits a velocity-proportional dependence but deviations have been demonstrated for the energy loss of protons in Ge,

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Cu and Au [11–13]. However, in a nonadiabatic model, Correa et al. [14] have demonstrated a nontrivial connection between the ESP and the nuclear stopping power. State-of-the-art calculations have been performed for protons slowing down in insulators and noble metals using time-dependent density functional (TD-DFT) [15]. Such calculations have managed to describe the expected threshold velocity for Au, due to the role of the d electronic orbit, that causes a significant deviation from the expected velocity-proportional dependence.

The vast majority of recent developments is conducted for proton projectiles in many different media. Few pieces of information are known for heavy ion projectiles, due to both theoretical difficulties that must be circumvented and to the few experimental data available. In this paper, we present new experimental data for the energy loss of Ti, V, Cr ions in Ge and Au targets in the 150–500 keV/u energy range. The stopping power of Ti in Au has been measured previously [16], and it is included here for the sake of comparison with the Ti in Ge target data. Ge and Au were chosen as targets since they exhibit different electronic configurations in the outermost shell, which might affect the ESP for heavy ions. Moreover, accurate knowledge of the stopping power in Au is important in nuclear structure experiments since it is often used as a stopper medium [5,17]. Demands for accurate predictions and the absence of a valid theory for the vast projectile-target-energy phase space make semi-empirical modeling a useful approach. The Northcliffe and Schilling (NS) tables [8] and the SRIM code, based on the Ziegler, Biersack and Littmark procedures [9], are often used for quantitative purposes in applied sciences. Nevertheless, they may contain significant discrepancies between predicted and measured values for high-Z projectiles due to limitations in the extrapolation of the physical description and limited experimental data available for heavy ions. Therefore, we compare our experimental results to the following theoretical and semi-empirical methods: i) the Unitary Convolution Approximation (UCA) [18,19]; ii) the Binary Theory (BT) [20]; iii) NS tables [8] and iv) SRIM code [21].

## 2. Experimental setup and results

Measurements were carried out at the 8UD-Pelletron Tandem of the University of São Paulo using the elastic scattering technique [22]. The experimental setup is depicted in Fig. 1. Elastic scattering between projectiles, from an energetic beam, and heavy atoms, that compose the thin primary foil, produces heavy ions at low energies. Recoiling atoms, from the primary foil, in kinematic coincidence with the scattered primary particles are the heavy projectile of interest at low velocities. Particles were detected using Si detectors: two of them placed at $\theta_{lab} = 45°$ and 60°, as monitors, and the third one placed on a mobile platform. The monitors, for the detection of the scattered particles of the primary beam, were set about 210 mm from the primary target and with an 8 mm collimator, corresponding to a solid angle $\Omega \sim 1.1\,\text{mrad}$. The third one, used to detect the recoiling atoms, was mounted 120 mm from the primary foil with a 3 mm collimator ($\Omega \sim 0.5$ mrad). The heavy projectile energy depends on the primary beam species, their energy and the scattering angle. The elastic scattering of either $^{16}$O or $^{28}$Si at 45°, for instance, produces recoiling particles at different angles. The recoiling angles of the secondary heavy ion beam were found experimentally by determining the maximum of the angular distribution of the recoils, without the secondary foil, in time coincidence with each monitor. Kinematic broadening due to the finite solid angle of the detectors introduce an uncertainty of about 3.5% in the energy of the recoiling particles.

Secondary foils of Ge and Au were mounted on a six-position target holder that moved the targets into and out of the secondary beam. Two positions were left empty for the measurements of the energy of the recoiling particles. The system was placed as close as possible to the detector (less than 5 mm apart) to avoid missing particles due to the angular straggling caused by the secondary target. In this way, we measured the total stopping power, which is composed of the contribution from the electronic and the nuclear stopping. However, for the energies investigated here, the nuclear component is negligible, according to the SRIM code [21]. Henceforth, we refer to our data as ESP.

Energy calibration of the detector for heavy ions is described in detail in Ref. [22]. The experimental data measured without the secondary target in front of the detector were used to build the calibration curve. An example of the energy calibration is shown in Fig. 2. The energy is determined using a Monte Carlo (MC) code that randomly selects the point of elastic scattering within the primary target and calculates the energy losses of the primary beam in the incoming trajectory and the secondary ions in the outgoing trajectory. Stopping powers from [9] are used as inputs to the MC code. Fig. 2 shows a typical calibration curve for the Ti foil with $99\,\mu\text{g/cm}^2$ thickness. The calibration curve is linear in the enegy range inspected. Nevertheless, we highlight the importance of using thin primary foils to minimize systematic errors in the estimation of the energy loss of heavy atom recoiling in the foil.

The Ti, V and Cr primary targets and Ge and Au secondary targets are self-supported foils produced by vacuum evaporation. Their thicknesses were determined by the energy loss of $\alpha$ particles from a $^{241}$Am source. Thickness of the foils are shown in Table 1. Uncertainties in the thickness are mainly from the stopping power of the $\alpha$ particles (estimated in 4%). We evaluate the foil uniformity by measuring the thickness at several points, in both vertical and horizontal directions using a one-millimeter pin–hole cover in front of the $^{241}$Am source. The non-uniformity, defined as the standard deviation of the measured

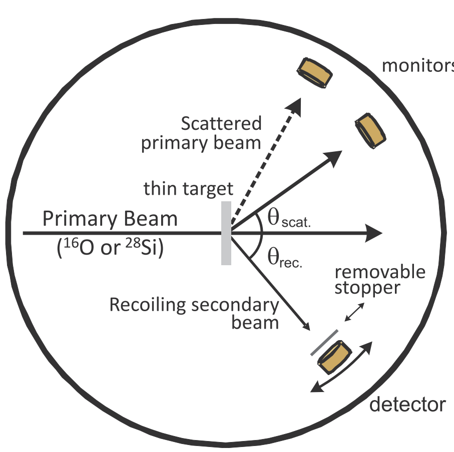


**Fig. 1.** Experimental setup used for the measurements of the energy loss of Ti, V and Cr in Ge and Au at energies below 500 keV/u. We used $^{16}$O and $^{28}$Si as primary beams with energies between 32 and 58 MeV, usually with 300 nA beam current.

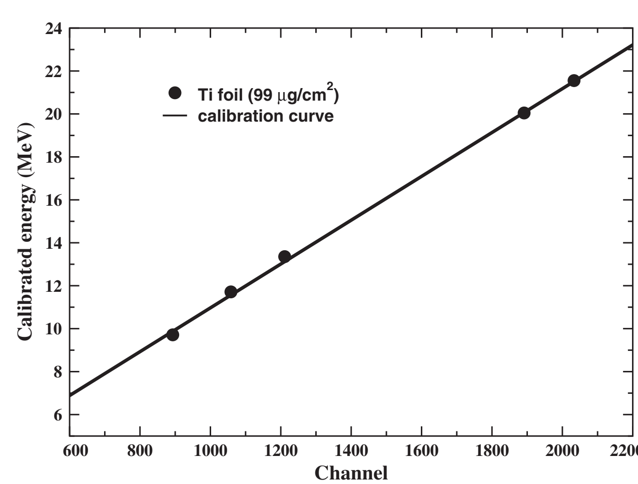


**Fig. 2.** Energy calibration curve of the detector for Ti ions. See text for details.