Stopping power of Au for Cu ions with energies below Bragg's peak

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Abstract

The stopping power of Au for Cu in the energy range $6 < E < 25$ MeV was measured using a secondary beam of low velocity heavy ions produced by elastic scattering of an energetic primary beam (typically ^{28}Si or ^{16}O) on a natural Cu target. The results were compared to predictions of the Lindhard, Scharf and Schiott (LSS) theory, the Binary Theory (BT), and the Unitary Convolution Approximation (UCA) and also to semi-empirical predictions such as the Northcliffe and Schilling tables and the SRIM2003 computer program.

Key words: Stopping Power; Heavy Ions; Low Energy
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1 Introduction

The present understanding of the phenomena of the slowing down of heavy ions in matter at intermediate and low energies is continuously improving, both in the theoretical and experimental aspects. Nonetheless, the complexity of the situation, involving excitation and ionization of both the penetrating ion and the constituents of the stopping medium, still makes the theoretical description less useful for accurate quantitative predictions, even with promising new approaches, such as the Binary Theory (BT) [2] and the Unitary Convolution Approximation (UCA) [3]. Semi-empirical calculations [4, 5] are still used to predict the stopping power for a large range of the (v, Z_1, Z_2) space. For lighter projectiles (e.g. C, N, O) and for a restricted variety of stopping media, for which experimental data are more abundant, these semi-empirical predictions are, in general, of good accuracy. For heavier ions, especially at low

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energies where experimental information is still scarce, even these predictions can fail for many projectile-stopper combinations.

An accurate knowledge of the stopping power of solids for heavy ions in the low velocity region is necessary in many applications, such as ion implantation and material analysis techniques, e. g. Elastic Recoil Detection Analysis (ERDA) and Rutherford Backscattering Spectroscopy (RBS) [6]. In the Doppler Shift Attenuation Method (DSAM) for measuring pico second nuclear lifetimes [7], the precision of the results is, in many cases, limited by the inaccuracy of the stopping power used in the analysis. In particular, a series of high quality nuclear lifetime measurements using this technique for nuclei in the Ti, V, Cr region [8–10] was developed in recent years, calling for new stopping data of low velocity (v/c $\sim$ 1-5%) projectiles in that region, especially for stoppers such as gold and lead, the ones most commonly employed in the DSAM technique.

In this work we present measurements of the stopping power of Au for Cu at energies ranging from 6 to 25 MeV, where no experimental data were previously available. Our experimental results are compared to the well established LSS theories, to the recently proposed BT [2] and UCA [3] theories as well as to widely used semi-empirical predictions [4, 5].

2 Measurements and Analysis

The experimental data were obtained at the 8UD-Pelletron tandem facility of the University of São Paulo using a technique recently developed by our group [11] in which a heavy ion beam at low energies (Cu in the present case) is produced by elastic scattering of a primary accelerated beam on a thin target. Here we used primary beams of ^{16}O and ^{28}Si with $\sim$ 300 nA on a Cu target. The Si detector for the scattered primary beam was positioned at $\theta_{scat} = 60^o$ with a total angular aperture of about 2^o. For detecting the secondary beam, composed of recoiling atoms from the target in kinematic coincidence with the scattered primary particle, a Si detector was placed in a mobile platform, at 120 mm from the Cu target and 1.5^o of total angular aperture. The kinematic angle for the secondary beam was found experimentally by determining the maximum of the angular distribution of the recoils, measured without the stopper foil. It should be highlighted that this recoil angle is independent of the energy of the primary beam. The stopper foil was placed in a holder which could be moved into and out of the secondary beam during measurements.

The Cu target and the Au stopper were produced by vacuum evaporation and their thicknesses (156$\pm$6 and 540$\pm$20 μg/cm^2 respectively) were determined by measuring the energy loss of α particles from a ^{241}Am source. The stopping power used for the 5.48 MeV alpha particles in Cu and Au are respectively, 0.409 and 0.226 MeV.cm^2/mg [17]. Uncertainties in the foil thickness are mainly due to the uncertainty in the α particle energy loss (4%). The non-uniformity of the Au stopper, defined as the maximum variation of the thickness with respect to the average value, was less than 2% when measured in two perpendicular directions on the foil.

In order to calibrate the energy scale of the secondary beam detector, we measured the pulse height spectra without the stopper foil for all experimental points, since the dead layer of the detector window may affect charge collection and the linearity of the energy-channel relation for low energy ion. The energies of the ions emerging from the target were predicted using a Monte Carlo procedure which takes into account all the parameters of the experimental geometry [11]. One relevant point in the simulation is the estimate of the energy loss of the Cu ions in the target itself. One must employ thin targets, typically < 0.2 mg/cm^2, so that the corrections for the stopping power of Cu in Cu are rather small and results are not critically dependent on the accuracy of the stopping power used in the simulations. Typical energy spectra of the Cu particles with and without the absorber foil are shown in Fig. 1. An asymmetric curve (gaussian plus exponential tail in the low energy side) was fitted to the peaks in order to obtain the average energy of the Cu particles. This energy was also obtained by simply calculating the centroid of the experimental distribution. Even though the energies obtained from each method are slightly different, the differences used to compute the energy loss, calculated with the two methods are consistent within the predicted uncertainties.

Since the fraction of the initial energy of the Cu ions lost in the Au foil is quite small ($<$15%), the differential approach was used to extract the experimental stopping power:

$$\frac{dE(\overline{E})}{dx} \approx \frac{\Delta E}{\Delta x}$$

At the lowest energies measured, nuclear stopping becomes a relevant process of energy loss. Due to the limitations imposed by the angular aperture of the particle detector, secondary ions which suffer multiple elastic scattering within the stopper, resulting in a large exit angle with respect to the incident direction, cannot not be detected. Those particles correspond to the highest energy losses within the stopper, so the energy loss measured is slightly lower than it should be. Using the Monte Carlo procedure described above, a correction for these events can be obtained. The ratio between energy losses obtained in simulations with the detector placed very close to the stopper and that at the position used in the experiment was applied to correct the experimental data. In the worst case, Cu ions at 6.3 MeV, the correction was $\sim$ 6%. For the points above 9.4 MeV, this correction was less than 1%. The stopping power resulting from the present measurements (including the solid angle correction) are shown in Table 1.

3 Discussion

In order to compare the present results with theories for the electronic stopping power, we subtracted, from the data, the nuclear stopping predicted by Biersack et al [4]. The amount subtracted was up to 13% for the points at lower energies, and decreased to $\sim 1\%$ for those at higher energies.

3.1 Stopping Power Theories

The well known theory for the stopping of heavy ions at low velocities, developed by J. Lindhard and co-workers in the late 1950s, describes both the electronic and the so called nuclear components of the energy loss process (the LSS theories) [12, 13]. For the electronic part, the theory considers the energy loss of a charge Z in a free electron gas and makes use of the local density approximation for the case of real atoms. For low velocities it predicts a linear relationship between the ion's velocity and the electronic stopping power [12]. While the general trend of the stopping cross-section is well described by the LSS theory, the linear relation to the ion's velocity is not observed in most of the cases. The discrepancies for particular situations can be empirically accommodated, allowing for variations from the linear relation by using the expression:

$$\left.\frac{dE}{dx}\right|_{\text{el.}} = kE^p$$

where k and p are adjustable parameters. In general, experimental values for the exponent p are larger than predicted by the LSS theory [14, 15]. For the present case, also the LSS expression cannot reproduce the experimental data, but they can be well described by the above expression taking into account $k = 0.53$ and $p = 0.83$ (obtained by a least square fit procedure), as shown in Fig. 2.

In recent years, several new approaches for describing the electronic part of the energy transform mechanisms have appeared in the literature. Two of them, applicable to heavy ions, will be considered here; the binary theory (BT) [2] and the unitary convolution approximation (UCA) [3]. The physical model of BT is very close to the classical model developed by N. Bohr in 1913 [1], the main differences being the avoidance of a perturbation expansion and no distinction between close and distant collisions. Also, it incorporates several ingredients that are of relevance for the case of heavy ions, such as screening, high-order Z_1 effects, shell corrections and energy transfer by excitation and ionization of the projectile. The UCA [3,16] is based on impact parameter energy transfer expressions for close (two body) and distant (dipole) collisions, with interpolations for intermediate impact parameters. From the basic expressions for the stopping of a bare charged particle, a detailed description of the projectile-screening function is introduced for the case of heavy ions. Using reliable atomic electron densities and oscillator strengths, the theory predicts the electronic stopping power for a broad range of velocities.

In Fig. 2 we compare our data to predictions given by the binary theory and the unitary convolution approximation where we also include the data from ref. [18]. As seen in the figure, the BT curve is systematically above the data, not only for the region of the present measurements, but also for the higher energies of the data from [18]. The predictions for the UCA model were calculated using the Casp 3.1 program [16]. The UCA curve fits very well our data set, but for higher energies it underestimates the data. One reason for that may be related to the Barkas effect, not included in the present version of the UCA model. Even though the UCA model seems successful for our present low energy data, the comparison for Ag stopping in Au, in a similar velocity range [11], showed a deviation of $\approx 30\%$.

3.2 Semi-empirical Stopping Power Predictions

One of the most successful semi-empirical formulations, for a large range of the (v, Z_1, Z_2) space, was developed around 1970 by L.C. Northcliffe, R.F. Schilling (NS) [5], and is still widely used. In the 1980's, J.F. Ziegler, J.P. Biersack, U. Littmark [4] published a similar formulation for a larger range based on a much larger quantity of experimental data. This new semi-empirical formulation took into account the so called Z_1 and Z_2 oscillations in the stopping cross-sections at low velocities, not present in the NS tables. This formulation have been implemented in the computer code SRIM [17]. A comparison of our data and the NS tables and the SRIM code (version 2003.26) predictions is shown in Fig. 3. The NS prediction overestimates the stopping power for energies below $\approx$ 10 MeV and underestimates it for energies above $\approx$ 30 MeV. The average deviation is 13%, reaching 28% at energies below 10 MeV. The good agreement of the SRIM prediction with the data from [18] is expected since that code version includes these data in its database (see 3). The extrapolation method used in SRIM to lower energies overestimates the stopping power and the deviation reaches 25% for energies below 10 MeV .

4 Conclusion

In this work, we present new data for the stopping power of Au for Cu ions for energies in the range 6-30 MeV. Comparisons to theoretical models showed that BT and UCA are promising theories for describing the electronic energy loss processes for heavy ions at low energies. In the case of the semi-empirical description, despite the lack of extensive experimental data for heavy ions at low and intermediate energies, the quality of predictions for the present case is quite reasonable. For the case of the NS tables, Au was one of the stopping media used for the construction of the tables, so the oscillatory behavior with respect to Z_2, not included in that formulation, should not affect appreciably the predictions. For the SRIM case, an average deviation of 6% between the data base and the fitted curves is predicted. The average deviation in the case of the present data is also near this value, except for the points at the lowest energies.

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5 Figures

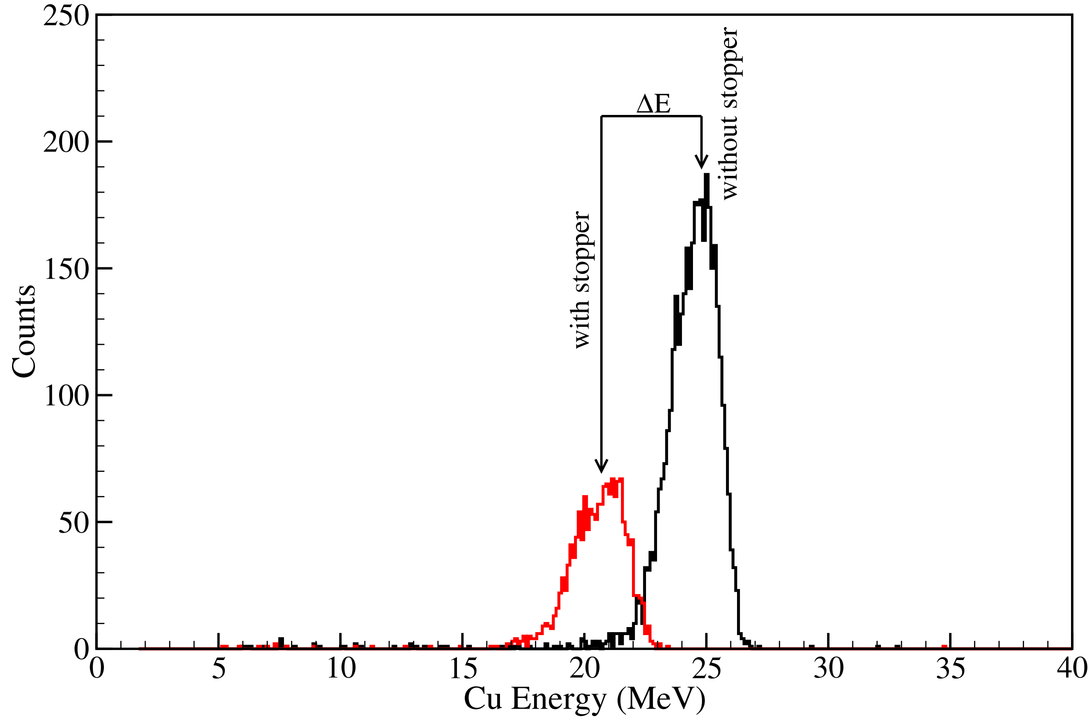

Figure 1. Energy spectra of Cu ions with and without the Au stopper foil.

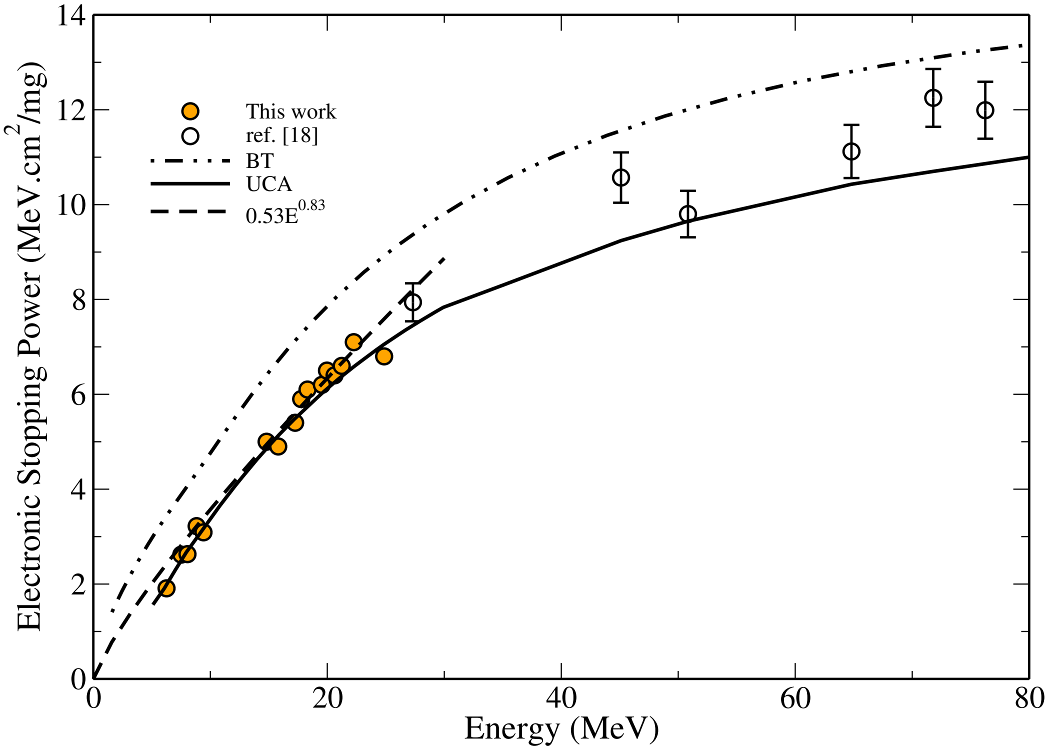

Figure 2. Comparison between experimental electronic stopping power (see text) and theoretical predictions from the Binary Theory (BT) and the Unitary Convolution Approximation (UCA) for Cu in Au. Also shown, the modified LSS expression fitted to the experimental data.

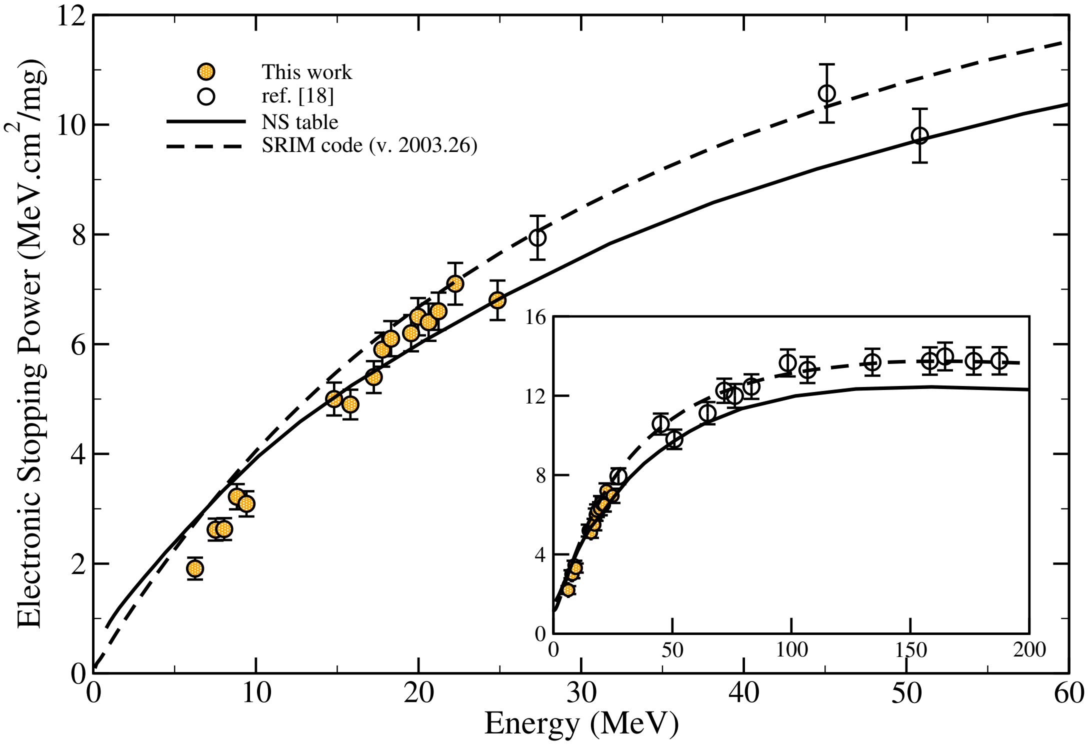

Figure 3. Experimental electronic stopping power for Cu in Au compared to semiempirical predictions (NS table and SRIM code). Inset, an extension to higher values of the plot.

6 Tables

$\overline{E}$	dE/dx_{exp}	$\overline{E}$	dE/dx_{exp}	$\overline{E}$	dE/dx_{exp}	$\overline{E}$	dE/dx_{exp}
24.8(4)	6.9(4)	20.0(3)	6.6(3)	17.3(3)	5.5(3)	8.83(11)	3.45(18)
22.4(4)	7.2(4)	19.5(3)	6.3(3)	15.8(3)	5.1(3)	8.05(11)	2.87(15)
21.2(4)	6.6(3)	18.3(3)	6.2(3)	14.8(3)	5.2(3)	7.52(11)	2.87(15)
20.6(3)	6.5(3)	17.8(3)	6.0(3)	9.42(11)	3.31(18)	6.26(10)	2.19(13)

Table 1
Experimental data of total stopping power of Au for natural Cu ions (M=63.55 amu), including the solid angle correction. $\overline{E}$ is given in MeV and dE/dx_{exp} in $MeV/mg/cm^2$. In the uncertainties shown for the stopping power is included the error in the stopper foil thickness (see text).