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Threshold effect in the energy loss of hydrogen and helium ions transmitted in channeling conditions in gold single crystal

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Abstract

The energy loss of hydrogen and helium ions in the low energy range (<10 keV/u) in single crystal gold targets is investigated experimentally. We found that the stopping power for helium ions shows a deviation from the proportionality with ion velocity predicted theoretically. This behavior has been also observed for protons in previous experiments. Additionally, we found that for a small range of velocity the energy loss for helium ions has the same magnitude as for protons for the same velocity. This last finding is in agreement with early theoretical prediction for the ion energy loss interacting with low electron densities, beyond of metallic densities, in the frame of the free electron gas model and the density functional theory. Both effects are explained due to two particular phenomena: particle channeling in monocrystalline targets, where the inhomogeneity of the spatial electron density distribution plays a fundamental role and the well-known threshold effect in the stopping power which is explained considering the electronic band structure properties of metallic targets.

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Keywords: Channeling; Energy loss

1. Introduction

The study of the interaction of ions with crystalline solids is an active area of physics and a source of multiple technological applications when these effects are studied at the nanoscale range. There are some fundamental issues that in the low particle velocities regime are still unknown and where more precise experiments are needed. The main energy loss mechanism for ions in metallic targets is the excitation of valence electrons, which can be considered as a free electron gas. Is well known from the theoretical point of view the electronic energy loss for charged particles at low velocities is proportional with the ion velocity [1–4], described by

$$\frac{dE}{dt} = -Q(n)v. \tag{1}$$

Here, Q is the friction coefficient and depends on the mean electron density of the target n, and v the mean ion velocity. In the case of gold the friction coefficient for protons is approximately 0.31 a.u., and for helium ions is approximately given by 0.74 a.u. These friction coefficients are obtained using an r_s value of 1.5 a.u., corresponding to gold mean electron density n. In the free electron model, this parameter is given by

$$r_s = \left(\frac{3}{4\pi n}\right)^{1/3}. \tag{2}$$

Several and recent experiments have demonstrated that this behavior does not hold for protons and deuterium interacting with metals, particularly in transition metals as Cu, Ag, Au and Pd [5–8]. This phenomenon has been attributed to an energy transfer threshold to the target electrons and is explained considering the electronic valence band structure for those metals which differ from those of free electrons as the case of aluminum [9,10]. In our experiment we have studied the electronic energy loss

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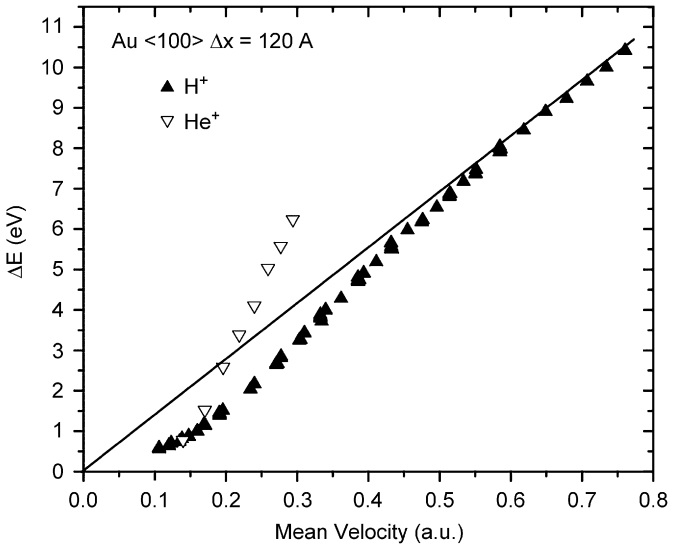

Fig. 1. Energy loss of protons and helium ions transmitted through the ⟨1 0 0⟩ direction of a single crystal gold thin foil of 120 Å.

for protons and helium ions, transmitted through thin films of monocrystalline Au in the ⟨1 0 0⟩ crystal direction, for incident energies ranging from 1 to 10 keV/u. The experimental setup has been described in a previous work [11]. All our measurements were performed using a ion beam from a hot discharge ion source which is focused by an electrostatic lens system and mass selected by a Wien velocity filter. Ion energy was analyzed using a 160° spherical electrostatic analyzer with a resolution less than 1%. The associated error in the energy loss determination was less than 3%. System detection consist in MCP detector plus electronic. The chamber collision was maintained at a pressure of 10^{-7} Torr during the experiment. Single gold targets were obtained from a commercial source.

In Fig. 1 we show the energy loss ΔE , in eV units, for protons and helium ions as a function of the mean velocity of the ions in the foil, in atomic units. This mean velocity is given by

$$\langle v \rangle = \tfrac{1}{2}(v_{\text{in}} + v_{\text{out}}). \quad (3)$$

In the plot, full triangles represent the energy loss for protons and open triangles helium energy loss. Lines represent the energy loss for protons (full line) and helium ions (dot line), from the well accepted model of the free electron gas predicted through Eq. (1).

From our experiment we obtain a new result that provides evidence of threshold effect for the energy loss for helium ions. This behavior has not been reported previously in any similar experiment. This last result is in total disagreement from the predicted linear behavior for ion energy loss as show in Fig. 1. Additionally, we found an additional important issue when we compare the energy loss for hydrogen and helium ions at the same velocity. At very low velocities we found that the helium energy loss has the same magnitude as for protons. This last finding is in agreement with early theoretical prediction for the ion energy loss interacting with low electron densities, beyond of metallic densities, in the framework of the free electron gas model and the density functional theory [4].

As conclusion, we observed a new non-expected behavior for helium and proton energy losses as a function of mean velocity in thin films of gold.

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