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Electronic stopping power of antiprotons for transition metals

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INTRODUCTION & AIM

The electronic stopping power of charged particles is a key parameter describing their slowing down, energy transfer, and penetration range in matter [1]. It plays a crucial role in diverse fields, including nuclear reactor design, ion beam analysis, ion implantation, radiation damage studies, molecular fragmentation, and hadron therapy. In particular, the **antiproton stopping power** provides a stringent test for theoretical models that operate under charge-conjugation symmetry. The difference between proton and antiproton stopping powers, known as the **Barkas effect**, remains an active topic of research and discussion [2].

In this work, we evaluate a non-perturbative model developed by our group [3,4] to describe the **stopping power of transition metals (Ni, Cu, Ag, and Au) for low-energy antiprotons**. It is based on the momentum distribution function of the **target's valence (free electron gas, FEG) and subvalence d-electrons**, combined with a fully relativistic solution of the electronic wave functions for transition metals with Z > 40, Ag and Au. **The model's predictions are compared with available experimental data [5,6], with special attention to the cases of Ni and Au, with measurements at very low impact velocities.**

METHOD

Non perturbative model [3]

The electronic stopping cross-section, SCS, can be express as:

$$SCS = \frac{2}{(2\pi)^3}\int \mathrm{d}\vec{p}\; f(p) v_r \frac{\vec{v}_r\cdot\vec{v}}{v}\sigma_{tr}(v_r),$$

where $\mathbf{v_r}=\mathbf{v}-\mathbf{p}$ is the relative velocity, $\mathbf{p} = \mathbf{v_e}$ is the electron momentum and velocity in atomic units, ***f(p)* is the momentum distribution function of target electrons**, σ_{tr} (v_r) is the transport cross-section,

$$\sigma_{tr}(k) = \frac{4\pi}{k^2}\sum_{l=0}^{\infty}(l+1)\sin^2[\delta_l(k)-\delta_{l+1}(k)],$$

$\delta_l(k)$ are the phase shifts in a central screened potential V(r), that dependents on the density of target electrons and the velocity of the projectile,

Screened potential

$$V_Z(r) = -\frac{Z}{r}(V_1 e^{-\mu_1 r} + V_2 e^{-\mu_2 r}),$$

Cusp condition at the origin

$$-2Z = \lim_{r\to 0}\frac{\frac{d}{dr}n_i(r)}{n_i(r)+n_0}.$$

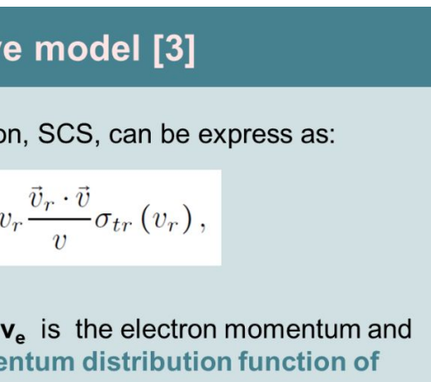
← IMPORTANT FOR ANTIPROTON IMPACT!

Momentum distribution functions:

- **FEG** $f(p) = \theta(p - p_F)/n$ with n being the atomic density of the target.
- **Bound d-electrons**

$$f(p) = \frac{(2\pi)^3}{2}|\Phi_{nd}(\vec{p})|^2,$$

with $\Phi_{nd}(\mathbf{p})$ being the Fourier transform of the wave function $\Phi_{nd}(\mathbf{r})$



f(p) for the FEG (light-grey area) and the 3d-subshell (red-solid curve) of Ni.

RESULTS & DISCUSSION

The present results for the stopping power of antiprotons in Ni and Au are shown in Figures 1–4. We also include proton impact values from Ref. [4] to highlight the antiproton–proton difference, known as the Barkas effect. The experimental antiproton data in these figures correspond to measurements performed at CERN [5,6], while the proton data are taken from the IAEA compilation [7].

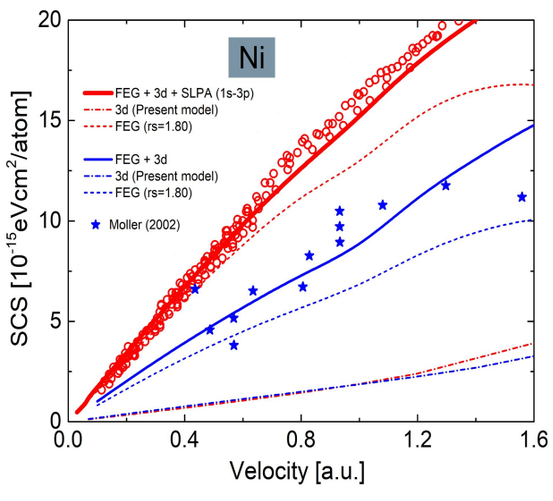


Figure 1: Electronic stopping cross sections of Ni vs velocity for antiprotons (blue) and protons (red). Line styles: solid (total), dotted (FEG), dash–dot (d-electrons). Symbols: antiprotons [5], protons [7].

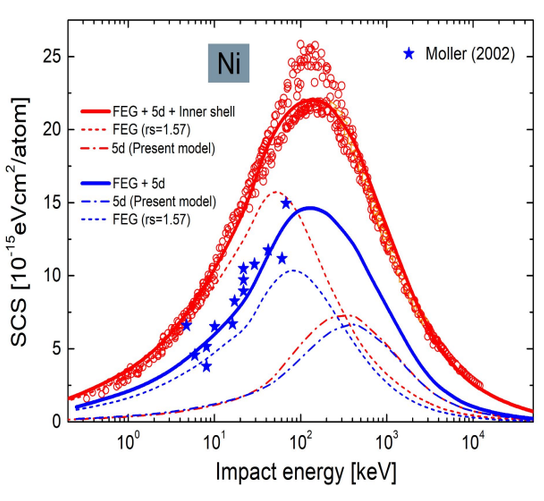


Figure 2: Electronic stopping cross sections of Ni vs energy for antiprotons (blue) and protons (red) up to 50 MeV. Lines and symbols as in Fig. 1.

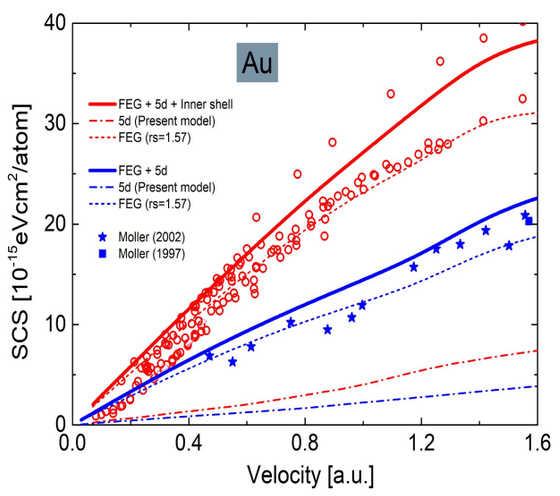


Figure 3: Electronic stopping cross sections of Au vs velocity for antiprotons (blue) and protons (red). Lines as in Fig. 1. Symbols: antiprotons [5,6], protons [7].

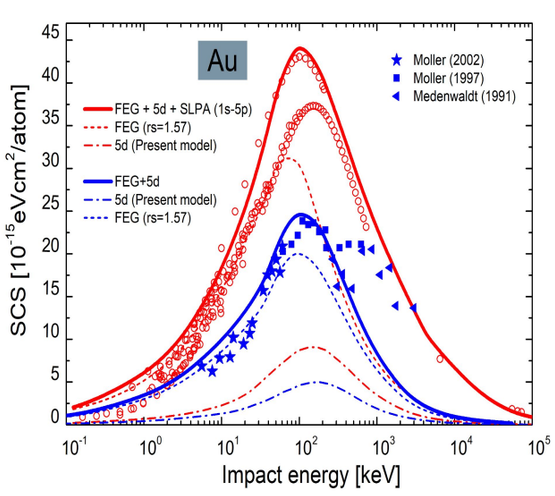


Figure 4: Electronic stopping cross sections of Au vs energy for antiprotons (blue) and protons (red) up to 100 MeV. Lines and symbols as in Fig. 3.

The present results describe the stopping power of antiprotons from very low impact energies up to the stopping maximum. Our total curves only consider the FEG and the d-subshell. It is suggested that, above 200 keV, inner-shell contributions play a significant role and should be included. Previous calculations by Sigmund [8] also reproduce the antiproton stopping power, but limited to impact energy above 10 keV.

CONCLUSIONS

We extend our model [3,4] for the stopping power of loosely bound *d* electrons in transition metals to the case of antiproton impact on Ni, Cu, Ag, and Au. The experimental values reported by the Møller group [5,6] are well described from very low energies up to the stopping maximum. We highlight the relevance of the *d*-electron contribution in describing the low-energy antiproton data.

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