



## Slowing down of 100 keV antiprotons in Al foils

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### ABSTRACT

Using energy degrading foils to slow down antiprotons is of interest for producing antihydrogen atoms. I consider here the slowing down of 100 keV antiprotons, that will be produced in the ELENA storage ring under construction at CERN, to energies below 10 keV. At these low energies, they are suitable for efficient antihydrogen production. I simulate the antihydrogen motion and slowing down in Al foils using a recently developed molecular dynamics approach. The results show that the optimal Al foil thickness for slowing down the antiprotons to below 5 keV is 910 nm, and to below 10 keV is 840 nm. Also the lateral spreading of the transmitted antiprotons is reported and the uncertainties discussed.

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Producing stable antihydrogen atoms at CERN will in the near future be based on slowing down antiprotons ( $\bar{p}$ ) with an energy of 100 keV (coming from the ELENA antiproton storage ring) to thermal energies [1,2]. One possible approach for achieving this is to use energy degrading foils [3].

Recently an approach to simulate the motion of antiprotons in materials with molecular dynamics was developed by me and coworkers [4]. As a brief summary, in that work we first used quantum chemical methods to determine the interparticle potential between antiprotons and nine different elements that may be used in energy degrading foils. The interparticle potentials allowed either determining the nuclear stopping power, or simulating the antiproton motion in materials with the molecular dynamics range calculation code MDRANGE [5]. For Si and Al, we also constructed an electronic stopping power valid down to low antiproton energies (for the other elements considered, there wasn't enough low-energy experimental data available to do this). Finally, we carried out systematic calculations of antiproton transmission through Si foils, that allowed determining the optimal foil thickness for antiproton slowing down to the energy ranges 0–5 keV, or 0–10 keV [4]. In this article, I present results for a similar optimization calculation for Al foils. Since these are readily available, not brittle, and electrically conductive, they can be even better suited for use as degrading foils than Si ones.

I simulated the transmission of antiprotons through Al foils using the  $\bar{p}$ -Al electronic stopping and interparticle potential developed in Ref. [4]. Otherwise the simulation procedure was

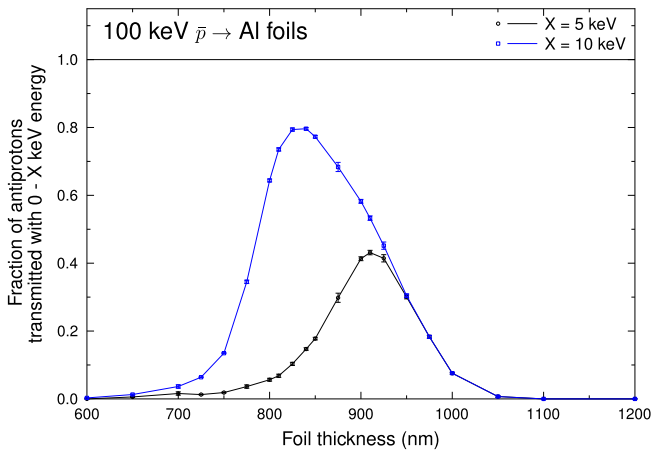
identical to that work, except that the MDRANGE simulation cell was crystalline Al. The antiprotons were coming in perpendicular to the Al crystal, aligned with a 100 surface normal. In principle this condition can lead to channeling [6]. However, the channeling effects were found to be very weak for Si [4], and tests showed that the same is also true for Al.

The results were analyzed with respect to the fraction  $f$  of antiprotons that were transmitted through a foil of thickness  $t$ , up to a maximum useful energy  $E_x$  that was either 5 or 10 keV. The function  $f(t)$  will have a maximum, since for a very thick foil almost all or most antiprotons will stop in the foil, and for a very thin foil they will transmit with energies much higher than  $E_x$ .

The results for  $f(t)$  are shown in Fig. 1. They show that for  $E_x = 5$  keV, the optimal film thickness is 910 nm, and for a  $E_x = 10$  keV is 840 nm. The lateral and movement direction distributions of the antiprotons on exiting the film is shown for these thicknesses in Fig. 2.

The results have a statistical uncertainty of about  $\pm 10$  nm due to limited statistics in the number of ions simulated. The uncertainty due to choice of interparticle potential was analyzed by rerunning the 900 nm case with the alternative interparticle potential fit provided in [4]. The results showed that the transmission probability is the same within the statistical uncertainty ( $0.413 \pm 0.006$  for  $E_x = 5$  keV) for both potentials. An additional possible source of uncertainty is the electronic stopping power. This was previously obtained in Ref. [4] based on data from Ref. [7]. The low-energy limit of the experimental data is based on rather few data points,

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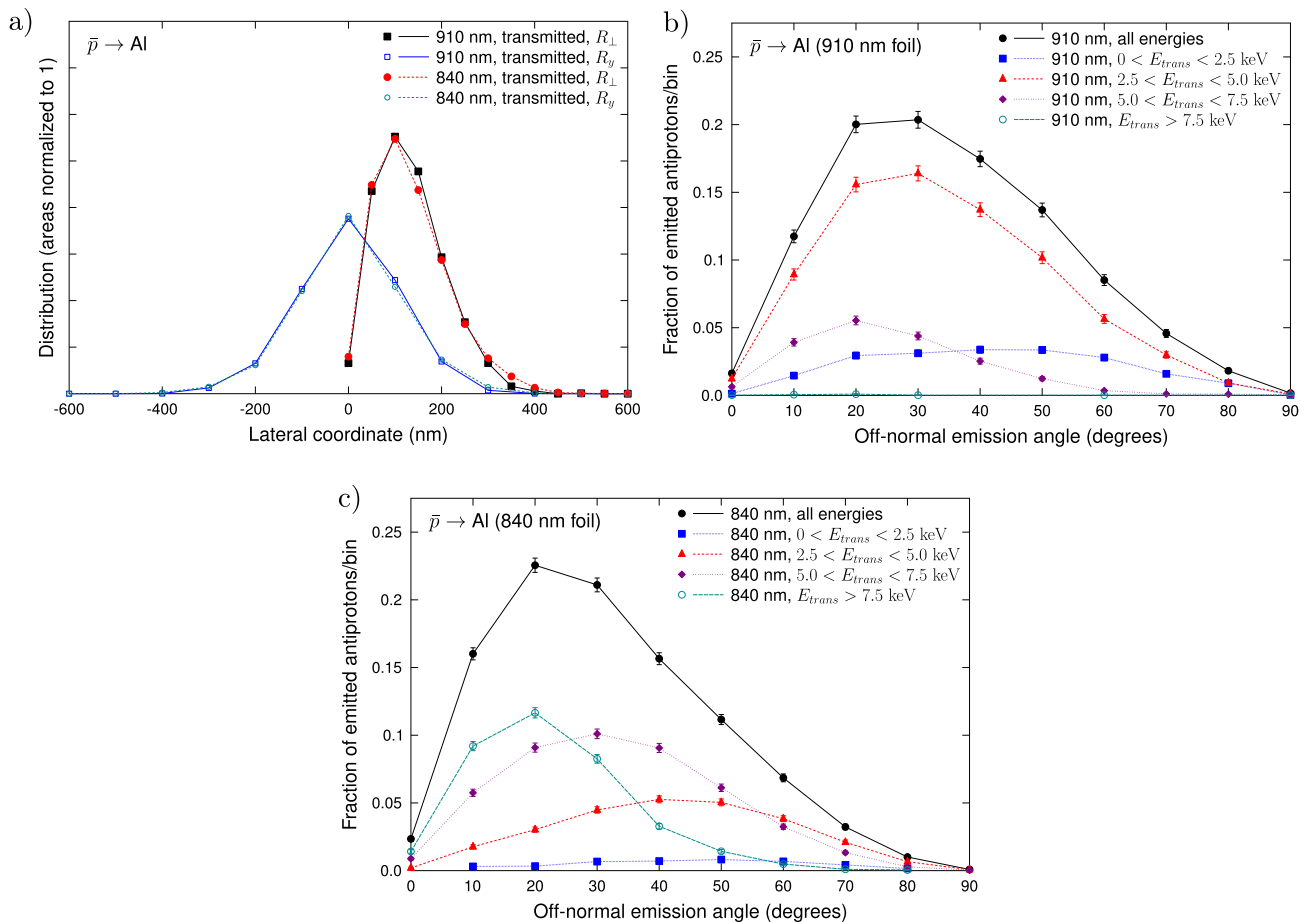


**Fig. 1.** Results for 100 keV particle transmission through Al foils of varying thickness  $t$ . The data shows the fraction of antiprotons that can be captured as a function of film thickness. Two cases for different possible experimental setups are shown: either the case for the maximum energy for antiprotons to be captured  $E_x$  is 5 keV or 10 keV.

which have some fluctuations. I reconsidered the electronic stopping fit by leaving out some of the low-energy data points and redoing the fit. From the standard deviation of the different fits, I found that the uncertainty of the electronic stopping is about 2%, i.e. introduces a systematic uncertainty of  $\pm 20$  nm.

The results on the lateral variation of the exit point show that this is almost always within 400 nm, i.e. microscopic, and hence not likely to be of consequence in a macroscopic experimental setup. On the other hand, the directions of the outgoing particles have a large angular variation, especially for the lower-energy ( $< 2.5$  keV) antiprotons that have almost half of the antiprotons moving in directions higher than  $45^\circ$  off-normal. This observation likely should be considered in the detailed design of antiproton trapping equipment.

In conclusion, I have determined the optimal film thicknesses for Al degrading foils for 100 keV antiprotons. For the upper energy limit for antiprotons that can be captured of 5 keV, the optimal film thickness is  $910 \pm 10_{\text{STAT}} \pm 20_{\text{SYST}}$  nm, and for the limit 10 keV,  $840 \pm 10_{\text{STAT}} \pm 20_{\text{SYST}}$  nm.



**Fig. 2.** Lateral and off-normal angle distributions of antiprotons with initial energy of 100 keV after exiting the Al foils. a) Lateral range  $R_\perp = \sqrt{x^2 + y^2}$  distribution as well as the distribution of the range in the y direction only,  $R_y$ . b) Exit angles for the optimal thickness of transmission in the 0–5 keV energy range, and c) for 0–10 keV.

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