First measurement of the antiproton-nucleus annihilation cross section at 125 keV

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Abstract The first observation of in-flight antiproton-nucleus annihilation at ~130 keV obtained with the ASACUSA detector has demonstrated that the measurement of the cross section of the process is feasible at such extremely low energies Aghai-Khozani, H., et al., Eur. Phys. J. Plus 127, 55 (2012). Here we present the results of the data analysis with the
evaluations of the antiproton annihilation cross sections on carbon, palladium and platinum targets at $\sim 125$ keV.

**Keywords** Antiproton · Annihilation · Cross section · Nuclear

1 Introduction

The ASACUSA Collaboration is performing a wide physics program at the Antiproton Decelerator (AD) at CERN, mainly focused to the hyperfine spectroscopy of the ground state of antihydrogen [2, 3] and to high resolution laser spectroscopy of antiprotonic helium [4, 5]. A part of the physics program is also devoted to perform measurements of the annihilation cross section ($\sigma_{ann}$) of low-energy antiprotons on nuclei.

The knowledge of the antinucleon $\sigma_{ann}$ at low energies is of interest both for nuclear physics studies (such as the search of nuclear resonances, the determination of the potential parameters, the investigation of the excitation process of the nuclear matter) and for the astrophysical studies of the matter–antimatter asymmetry in the visible universe.

Recently it has also been emphasized an abnormal behaviour [6] in the antineutron $\sigma_{ann}$ in disagreement with the expectations for a short range interaction like the strong interaction [7].

The ASACUSA Collaboration measured the antiproton ($\bar{p}$) $\sigma_{ann}$ on medium-heavy and heavy nuclear targets for the first time at 5.3 MeV kinetic energy [8, 9] and the results are in agreement with the expectations from the black-disk model with the Coulomb corrections.

Here we present the results of the antiproton measurement performed at around 125 keV, in an energy region where no data exist.

2 Measurement technique and experimental setup

Our method to measure the $\bar{p}$ $\sigma_{ann}$ in the 100 keV region is described in ref.[1]. Here we recall only the main features.

Some 25 % of the antiprotons delivered by AD at 5.3 MeV in bunches of $\sim 3 \times 10^7 \bar{p}$s are decelerated down to 130 keV by the ASACUSA radiofrequency quadrupole decelerator (RFQD) which is followed by the so-called dogleg magnetic beamline [10] which selects the momenta of the antiproton and by an electrostatic quadrupole. Then the $\bar{p}$’s enter inside a large vacuum chamber (170 cm in length, 120 cm in diameter) where a nuclear target is placed.

The target vessel is surrounded by two different detectors (called DET1 and DET2) made of several planes of scintillating bars to record the hits of the charged tracks emitted by the antiproton annihilations on the target. DET1 and DET2 have completely different light readout and electronics, while the scintillating bars are similar (only the sections and the lengths are different: $1.5 \times 1.9$ cm$^2$ and 96 cm for DET1, $1.7 \times 1.9$ cm$^2$ and 100 cm for DET2). DET1 consists of 10 planes with different numbers of bars (from 24 to 62) whose light is read by Hamamatsu 64 channels PMTs. The analog signals from the PMTs are acquired by dedicated frontend boards [11]. DET2 consists of two 50-bars planes. In this case the light is read by Hamamatsu MPPCs and dedicated frontend boards provide a full waveform acquisition [12].

The intensity of the $\bar{p}$ beam, whose annihilations occur mostly on the end wall of the target vessel, is monitored by a Čerenkov counter optimized for high dynamic range and its
linear response against pulsed beams containing $3 \times 10^7$ antiprotons has been demonstrated [13]. The Čerenkov detector is calibrated in a specific run with a ring placed downstream of the target and on the beam-axis. The method consists in counting the annihilations of the antiprotons diffused by the thin target on the ring since they depend on the number of antiprotons incident on the target, whose value can be easily determined by means of the Rutherford formula.

The annihilation cross section $\sigma_{\text{ann}}$ is given by:

$$\sigma_{\text{ann}} = \frac{N_{\text{flight}}}{N_p n_t}$$

where $N_{\text{flight}}$ represents the number of the in-flight annihilation events in the target of areal density $n_t$ and $N_p$ is the incident antiprotons number.

Since both the target signal and the Čerenkov detector calibration events are determined with the same detector (DET1 and DET2), the detector efficiency does not affect the $\sigma_{\text{ann}}$ evaluation.

The annihilation cross sections $\sigma_{\text{ann}}$ are calculated for the following targets: a $\sim 70$ nm bare-carbon foil, a $\sim 19$ nm Pd layer and $\sim 5$ nm Pt layer, all deposited on $\sim 70$ nm carbon foils.

After the data taking all the targets have been removed to measure their actual thicknesses by the Rutherford-backscattering technique (RBS). Unfortunately the bare-C target has been broken and it was not possible to measure it. The results show a good uniformity (better than 5%) and good agreement with the nominal thickness values.

3 Data analysis and cross sections evaluation

The red points in Fig. 1 and in Fig. 2 represent the signals from DET1 and DET2, respectively, when the targets are positioned on the antiproton beam axis, The black points are for the corresponding empty targets runs, that is when the target is substituted by its frame for background evaluation.

To be more precise, in Fig. 1 the histograms of the start time of the signal detected by the bars of one of the planes of DET1 are plotted while in Fig. 2 the histograms are for the times of the peaks found in the analog waveforms recorded for all the bars of DET2. The comparison between Figs. 1 and 2 shows a good qualitative agreement between the signals behaviours.

The target-region signal is clearly visible in the range $\Delta t = 1260 - 1380$ ns in both figures. The rise of the events after $\Delta t$ is due to the antiprotons annihilating on the lateral or final wall of the target vessel.

In the $\Delta t$ interval, in addition to the signal of in-flight antiprotons annihilations in the target, the following background contributions are expected:

1. $\pi-\mu-e$ decays due to the antiproton annihilations occurring at the end of the RFQD (a wall of concrete and iron blocks placed between the dogleg and the vessel screens only partially the detectors from this contribution);
2. antiproton annihilations on the target frame due to the beam halo;
3. annihilations at rest in the target or on the target support from the antiprotons scattered at angles close to $90^\circ$.
Fig. 1 Histograms of the times of the hits recorded by DET1: the red points are for the case of bare–C (a), C+Pd (b) and C+Pt (c) targets; the black points are for the corresponding empty target runs. The data at 1260–1380 ns represent the annihilation events coming from the target position while the rise at longer times is due to the annihilations on the end or lateral wall of the target vessel.

The contributions 1) and 2) are evaluated by using the events collected with the empty target runs, while the background of point 3) must be calculated by means of Monte Carlo simulations.

The latter depends on the elastic scattering cross-section and on the antiproton energy loss in the target material. At very low energies the Rutherford cross-section is expected to dominate the elastic nuclear cross-section [14]. The performed simulations are based on a modified GEANT3 package with an accurate description of the antiproton energy loss at very low energy (more details in [15]). For a $10^6$ antiprotons beam the evaluated numbers of antiprotons at rest in the targets and on the target support are (3, 0), (24, 2) and (13, 15) for the bare-C, C+Pd and C+Pt targets respectively.

The Monte Carlo simulations permit to determine also the energy loss of the antiproton beam inside the target. By considering that after the RFQD and the dogleg the 130 keV antiprotons have a large spread in energy ($\sim 15$ keV), the mean kinetic energy of the antiprotons annihilating in-flight results to be $125 \pm 15$ keV for the used targets.

The number of the detected tracks from the antiproton in-flight annihilations on the target is obtained by subtracting the evaluated background from the total tracks number in the selected $\Delta t$ range.
The latter information for one plane of DET1 is reported in Table 1, where the mean values per bunch of the detected tracks are listed after the normalization to the antiproton beam intensity of the C+Pt run.

The data reported in Table 1 show that the annihilations for the bare-C target are more copious than the annihilations for the other targets (C+Pd, C+Pt). This result looks strange since the C+Pd and C+Pt targets should contain the same annihilation contribution from carbon. In fact even if the bare-C target was not measured by RBS, its thickness should be similar to those of the carbon films of the C+Pd and C+Pt targets, since the method of preparing the targets is reliable as confirmed by the good agreement between the nominal values and the real values of those targets measured with RBS.

This surplus of annihilations is observed with both DET1 and DET2 detectors and in different days of data-acquisition. The most probable explanation is that a contamination of the bare–C target with some material deposition occurred during its installation in the vessel.

Since the data of the bare–C target are unreliable, we can use only the information from the other 2 targets. Starting from equation 1 and by using the annihilations counts measured

![Graphs](image-url)
Table 1  Mean values per $\bar{p}$ bunch of the charged track (prongs) counts on one of the scintillating detector

| Target          | prongs/bunch |
|-----------------|--------------|
| empty bare–C   | 0.75 ± 0.11  |
| bare–C         | 7.98 ± 0.27  |
| empty C+Pd     | 0.54 ± 0.07  |
| C+Pd           | 2.48 ± 0.13  |
| empty C+Pt     | 1.15 ± 0.16  |
| C+Pt           | 2.85 ± 0.14  |
| C+Pt+2ndF      | 9.63 ± 0.84  |

Plans of DET1. The reported values are normalized to the antiproton beam intensity of the C+Pt run. The “empty targets” are empty frames. The different targets (with the corresponding “empty targets” runs) have been used in different days with different $\bar{p}$ beam conditions. The C+Pt+2ndF case corresponds to the calibration run of the Čerenkov detector (see text) with a second ring placed 1.25 ± 0.2 cm downstream of the C+Pt target. The tracks count on the second ring is determined by subtracting the number of the C+Pt case from that of the C+Pt+2ndF case.

Fig. 3  Results of the measurement: the red and blue lines are the relations between the antiproton $\sigma_{ann}$ for Pt and Pd versus $\sigma_{ann}$ for C. The plotted points are the calculations at 125 keV from a black disk model including Coulomb attraction [16] (red for Pt, blue for Pd)

by DET1 and DET2 it is possible to express the $\sigma_{ann}$’s for Pd and Pt as functions of $\sigma_{ann}$ for C:

$$
\begin{align*}
N_{ann}^{(C+Pd)} &= N_{\bar{p}}^{(C+Pd)} \left( \sigma_{ann}^{Pd} n_{Pd} + \sigma_{ann}^{C} n_{C} \right) \\
N_{ann}^{(C+Pt)} &= N_{\bar{p}}^{(C+Pt)} \left( \sigma_{ann}^{Pt} n_{Pt} + \sigma_{ann}^{C} n_{C} \right)
\end{align*}
$$

(2)

In Fig. 3 the values of the $\sigma_{ann}$ on Pd ($\sigma_{ann}^{Pd}$) and on Pt ($\sigma_{ann}^{Pt}$) are plotted versus $\sigma_{ann}$ on C ($\sigma_{ann}^{C}$) as determined by (2).
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![Graph showing antiproton cross section measurements](image)

**Fig. 4** Antiproton cross section ($\sigma$) measurements at energies below 500 MeV. The full coloured bars are the ranges of possible $\sigma_{\text{ann}}$ values of the present measurement for C, Pd and Pt at $\sim 125\pm15$ keV with the condition that the $\sigma_{\text{ann}}$ function increases with the target mass number and decreases with the kinetic energy. The empty coloured bars represent the error (statistical+systematic). The plotted targets are: hydrogen (blue from ref. [17], red from ref. [18], green from ref. [19], black from ref. [20]), deuterium (blue from ref. [21], red from ref. [22], green from ref. [23]), He$^3$ (blue from ref. [24], red from ref. [21], black from ref. [25, 26]), Ne (green from ref. [27]), C (from ref. [28], red from ref. [29], Al (blue from ref. [28], black from ref. [31]), Cu (black from ref. [28], green from ref. [31]), Pb (red from ref. [31], black from ref. [32]), Ni from ref. [8], Sn from ref. [8], Pt from ref. [8]. All the data are for annihilation cross-section ($\sigma_{\text{ann}}$) measurements with the exception of those from ref. [22, 23, 25, 26, 28, 30–32] which are for the reaction cross-section ($\sigma_r$). In the selected $\bar{p}$ energy range, the $\sigma_r$ values are mainly due to the annihilation process ($\sigma_{\text{ann}}$) since the other processes (inelastic scattering, charge exchange, nucleon knock-out) contribute for a few percent only.

With the obvious request that the cross sections values are not negative, the ranges of possible $\sigma_{\text{ann}}$ values are: (0, 27±15) barn for C, (54±82, 192±82) barn for Pd and (0+266, 468±266) barn for Pt.

If the more stringent request that the $\sigma_{\text{ann}}$ function increases with the target mass number and decreases with the kinetic energy is applied by using also the existing data from other experiments (in particular the neon value at 57 MeV/c), the possible ranges of validity for $\sigma_{\text{ann}}$ are further reduced: (0, 22±15) barn for C, (76±82, 192±82) barn for Pd and (76±266, 468±266) barn for Pt. The quoted errors include both the statistical error of the measured counts and the systematic errors due to uncertainties on the target thicknesses, on the Monte Carlo simulations and on the position of the second frame in respect of the C+Pt target for the Čerenkov detector calibration. The latter uncertainty ($\sim \pm0.2$ cm) affects
directly the beam intensity measurement and represents the most relevant uncertainty for the \( \sigma_{\text{ann}} \) evaluation. For example with an error of \( \pm 0.1 \) cm the limits of the \( \sigma_{\text{ann}} \) values would decrease of \( \sim 25 \% \).

In Fig. 3 the calculations at 125 keV from a black disk model including Coulomb attraction [16] are also plotted. The comparison shows a good agreement between the experimental data and the model.

In Fig. 4 the results are plotted as full bands together with the existing \( \sigma_{\text{ann}} \) for different nuclei at energies below 500 MeV.

4 Conclusions

The limits of the antiproton annihilation cross section at \( \sim 125\pm 15 \) keV on C, Pd and Pt have been measured by the ASACUSA Collaboration. These measurements represent the only data achieved at these very low energies. The present results agree with the calculations from a black-disk model with the Coulomb corrections.

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