**Antiproton-nucleus annihilation studies**  
*(CERN-AD3/ASACUSA)*

**Abstract:** We plan [1] to conduct a systematic study of the charged multiplicity distribution in antiproton-nucleus annihilation at rest on various materials, by using a high resolution annihilation vertex detector.

The multiplicity distribution of charged annihilation products (such as pions, protons and nuclear fragments) is not well known for antiprotons annihilating at rest on nuclei. This information is an essential ingredient to Monte Carlo simulations (such as GEANT4), to model the background contribution in antihydrogen and low energy antiproton experiments. The current Monte Carlo simulations are performed with the CHIPS [2], the FRITIOF [3] or the FLUKA [4] packages. The former two were developed for high energy hadronic interactions. They are based on the interaction between parton constituents and are extrapolated to low energy antiproton annihilation (in spite of the fact that the low energy annihilation mechanism is still not understood in detail). FLUKA models the hadronic interaction at a higher level, i.e. in terms of resonance production and decay.

![Figure 1: Left: charged annihilation multiplicities for stopping antiprotons in copper and gold (dots with error bars), compared with Monte Carlo predictions from CHIPS, FTFP (FRITIOF) and FLUKA. Right: average multiplicities of minimum ionizing particles (top) and nuclear fragments (bottom) for copper, silver and gold, compared with Monte Carlo predictions (data obtained with nuclear emulsions, see [7]).](image)

Until very recently these models could not be verified, due to the absence of annihilation data. A few data points on antiproton annihilation at rest from experiments at the AD are now available [5, 6, 7, 8]. It is fair to say that none of the models is able to reproduce the data. For example, fig. 1 (left) shows the charged multiplicity distribution for copper and gold, and fig. 1 (right) the average charged multiplicity for copper, silver and gold, for minimum ionizing particles (essentially pions) and heavily ionizing annihilation products (p, α and nuclear fragments). FRITIOF (also called FTFP) is in clear disagreement and in particular grossly underestimates the number of nuclear fragments (also observed in [8]), CHIPS does not reproduce the distribution of heavy products. FLUKA performs...
somewhat better, which is perhaps not surprising since it models the interaction at the level of hadrons.

We intend to measure the multiplicity of minimum ionizing particles and that of nuclear fragments for antiprotons annihilating at rest on various elements across the periodic table. This will be performed by annihilating very low energy antiprotons on thin (\(\sim 1–5 \mu m\)) foils of various materials, such as Be (Z = 4), C (6), Si (14), Ti (22), Mo (42), Sn (50) and Au (79). The position of the annihilation vertex will be determined with a precision in the 10 \(\mu m\) range by a high resolution pixel detector capable of reconstructing the tracks of the annihilation pions and of measuring the energy deposited by nuclear fragments. We plan to use a Timepix3 detector obtained from the Medipix3 Collaboration, such as the one recently tested by AEgIS [9]. This was an ASIC hybrid detector module made of \(256 \times 256\) square \(55 \times 55 \mu m^2\) pixels. The detector thickness was 675 \(\mu m\), the dynamic range 4 – 500 keV/pixel and the time resolution 1.6 ns.

Figure 2: Left: annihilation of a 1 keV antiproton on the surface of the Timepix3 detector. The picture shows the emission of three minimum ionizing particles (pions) and of a nuclear fragment. The large energy deposit (Bragg peak) is clearly visible at the end of the track [9]. Right: reconstruction of the annihilation vertex on the surface of a foil located in front of the Timepix3 detector.

Figure 2 shows the typical energy deposited by a 1 keV antiproton annihilating on the surface of the detector. Annihilation on a thin foil placed close to the detector has also been tested by AEgIS and data are currently being analyzed. Preliminary results show that the annihilation vertex can be located with a precision of 25 \(\mu m\). Operation in vacuum has been tested at the level of \(10^{-7}\) mbar.

The annihilation measurements will be performed at the end of 2017, together with collaborators from NIKHEF involved in Medipix. We will use a matrix of 4 Timepix detectors covering a surface of about 9 cm\(^2\). For the operation in our experiment, the detector will be placed in an OVC enclosure separated from the UHV region by the foil under investigation (fig. 3 below). An antiproton rate of a few 100 sub-keV antiprotons, extracted from the MUSASHI trap during 10 s after every AD cycle, should be sufficient to obtain large statistical samples.

The position resolution along the beam axis of the current annihilation detector [10] will be improved by adding a scintillating fiber detector which will suppress the background from \(\bar{p}\) annihilation on the beam pipe (and also profit to the antihydrogen hyperfine structure measurement). We will add two layers of scintillating fibers, providing a resolution of typically 2 mm along the beam direction. This is sufficient to identify the
annihilation on the foil. A sketch of the layout is shown in fig. 3. We plan to use square fibers wound spirally around the detector axis, one layer (2 mm fibers) behind the inner scintillator layer and the other (1 mm fiber) around the beam pipe. Each fiber will be read out by SiPMs before being digitized.

Figure 3: Left: current annihilation detector. Right: upgraded detector equipped with fibers and the Timepix3 detector for annihilation studies. 1-Timepix3 detector, 2-thin foil to study the annihilation multiplicity, 3-vacuum pipe, 4-outer scintillator array, 5-inner scintillator array, 6 fiber detectors.

References