

# A method to polarise antiprotons in storage rings and create polarised antineutrons

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Received: date / Revised version: date

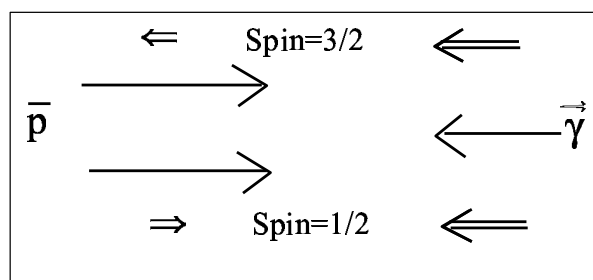
**Abstract.** An intense circularly polarised  $\gamma$ -beam interacts with a cooled antiproton beam in a storage ring. Due to spin dependent absorption cross sections for the reaction  $\gamma + \bar{p} \rightarrow \pi^- + \bar{n}$  a built-up of polarisation of the stored antiprotons takes place. Figures-of-merit around 0.1 can be reached in principle over a wide range of antiproton energies. In this process polarised antineutrons with polarisation  $P_{\bar{n}} > 70\%$  emerge. The method is presented for the case of a 300 MeV/c cooled antiproton beam.

**PACS.** 13.88.+e polarisation in interactions and scattering – 29.20.Dh Storage rings – 29.27.Hj polarised beams

## 1 Introduction

The preparation of polarised beams of nucleons and antinucleons at energies in the GeV region poses challenging technical problems. In the case of protons powerful sources of polarised protons exist. Starting from low energies a cascade of accelerators, all equipped with polarisation conserving beam optics, brings the proton beam to its design energy. Antiprotons, however, are produced with high energy proton beams. Large acceptance storage rings are used to collect and cool the produced antiprotons in order to prepare an antiproton beam for physics experiments. The exploitation of the polarisation degrees of freedom in physics experiments plays for antiproton and antineutron induced reactions a similar important role as for other probes *e.g.* electrons and protons. Challenging physics questions can be addressed with polarised antiproton beams as soon as moderate luminosities, compared to polarised proton beams, can be achieved. In recent publications [1–3] the physics motivations and foreseen experimental programs are addressed, previous studies to prepare a polarised antiproton beam are discussed and a method for the preparation of a polarised antiproton beam in the GeV region has been proposed [1]. In that proposal antiprotons would be polarised by the spin dependent interaction in an electron polarised hydrogen gas target. The antiproton beam polarisation  $P_{\bar{p}}$  would reach  $P_{\bar{p}}=0.2-0.4$ .

The method described in this paper makes use of different reaction cross sections for the two spin projections of antiprotons stored in a storage ring interacting with polarised  $\gamma$ -radiation. The main ingredients driving the method are described. Limits and possible future directions of the application of the method are addressed. Recent developments in accelerator physics paved the way to the proposed scheme. In sect. 2 the method will be de-

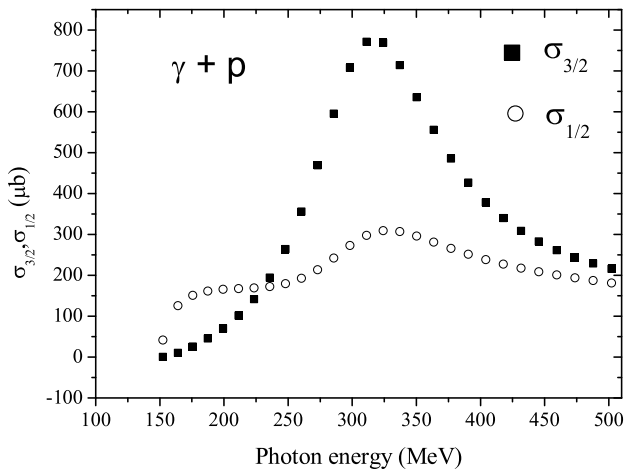


**Fig. 1.** The interaction of circularly polarised photons with stored antiprotons.

scribed. In sect. 3 the absorption cross sections will be presented. Sect. 4 deals with practical considerations for an implementation of the method. Sect. 5 addresses the question of preparing an antineutron beam. The article ends with a summary in sect. 6.

## 2 Method

The method makes use of the different sizes of total absorption cross sections for circularly polarised photons on the antiproton. The antiprotons stored in a ring equipped with a Siberian snake [4] traverse a straight section. By shining circularly polarised photons against a stream of antiprotons, see fig. 1, total absorption of the photons occurs, provided the photon energy  $E_\gamma$  exceeds the pion production thresholds of the reactions  $\gamma + \bar{p} \rightarrow \pi^- + \bar{n}$ , with  $E_{threshold}^{\pi^-} = 151.43$  MeV, and  $\gamma + \bar{p} \rightarrow \pi^0 + \bar{p}$ , with  $E_{threshold}^{\pi^0} = 144.68$  MeV. Due to the two possible total spin states of  $j=3/2$  and  $j=1/2$  two total absorption cross sections,  $\sigma_{3/2}$  and  $\sigma_{1/2}$ , come into play. The ideal situation



**Fig. 2.** The total absorption cross sections  $\sigma_{1/2}$  and  $\sigma_{3/2}$  calculated with the MAID program [5].

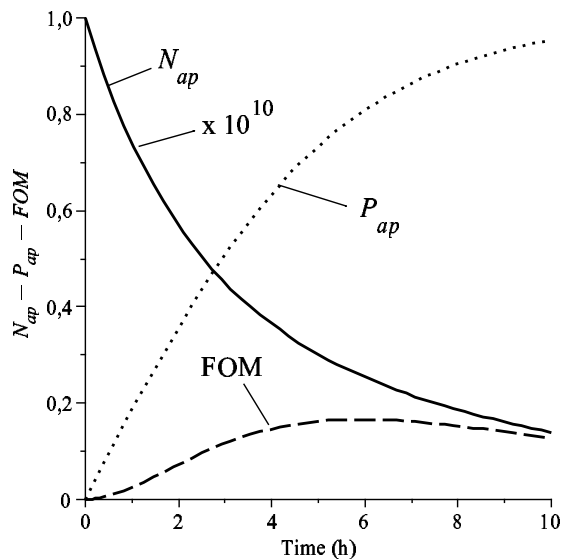
of the application of the method would be reached when one of those cross sections would be zero. Then the non disappearance of the other cross section would lead to the loss of that component of the beam in the ring, provided that the absorption process transforms the antiproton into an antineutron or, for the  $\gamma + \bar{p} \rightarrow \pi^0 + \bar{p}$ -reaction, the antiproton in the final state escapes the acceptance of the storage ring.

### 2.1 Cross sections, luminosity

Fig. 2 shows those total cross sections  $\sigma_{1/2}$  and  $\sigma_{3/2}$  as a function of the photon energy  $E_\gamma$  up to 500 MeV. Two energy windows can be seen that can be used to reach high polarisation. A beam polarisation

$$P(t)_{\bar{p}} = \frac{N(t)_{\bar{p}}^{1/2} - N(t)_{\bar{p}}^{3/2}}{N(t)_{\bar{p}}^{1/2} + N(t)_{\bar{p}}^{3/2}} \quad (1)$$

develops during the interaction period, with  $N(t)_{\bar{p}}^{1/2}$  and  $N(t)_{\bar{p}}^{3/2}$  as the stored antiprotons of the 1/2 and 3/2 channels, respectively. Close to the  $\pi^+$  and  $\pi^0$  production thresholds, around  $E_\gamma = 170 \text{ MeV}$ , a cross section ratio of 9 can be reached, thus, approaching almost the ideal situation. On top of the first antinucleon resonance  $\bar{\Delta}$ , a second window for an efficient beam polarisation opens up, a little bit wider on the energy scale than the first one yielding a cross section ratio  $\frac{\sigma_{3/2}}{\sigma_{1/2}}$  of 2-3. Reaction rates yield "decay constants" of the two components of  $a_{1/2}$  and  $a_{3/2}$ . As an example that sets the goal for the application of the method, values of  $a_{3/2} = 3.6 \cdot 10^{-5} \text{ s}^{-1}$  and  $a_{1/2} = 1.4 \cdot 10^{-4} \text{ s}^{-1}$  have been chosen. For those values of the decay constants and using a storage ring filled with  $N_{\bar{p}} = 10^{10}$  unpolarised antiprotons the number of the stored antiproton



**Fig. 3.** Built-up of polarisation  $P_{ap}$  and figure-of-merit (FOM) as well as a decreasing number of antiprotons in a storage ring.

develops in time as

$$N_{\bar{p}} = N_{1/2}^{\bar{p}} + N_{3/2}^{\bar{p}} \quad (2)$$

$$N_{\bar{p}} = 0.5 \cdot 10^{10} \cdot (e^{-1.4 \cdot 10^{-4} \cdot t} + e^{-3.6 \cdot 10^{-5} \cdot t}) \quad (3)$$

That development of  $N_{\bar{p}}$ , the built-up of the polarisation  $P_{\bar{p}}$  and figure of merit  $FOM = N_{\bar{p}}(t) \cdot (P_{\bar{p}}(t))^2$  are shown in fig. 3. At the maximum of the figure-of-merit with  $FOM = 0.18$  the number of stored antiprotons decreases to  $N_{\bar{p}} \approx 3 \cdot 10^9$  with a polarisation of  $P_{\bar{p}} \approx 0.62$ . In the ideal case, with only one absorption channel present, the figure-of-merit could reach a value of  $FOM = 0.5$ . Using the value of the decay constant  $a_{1/2}$  and taking the cross section, e.g.  $165 \mu\text{b}$  at  $E_\gamma = 190 \text{ MeV}$ , shown in fig. 2, the luminosity  $L$  results to:

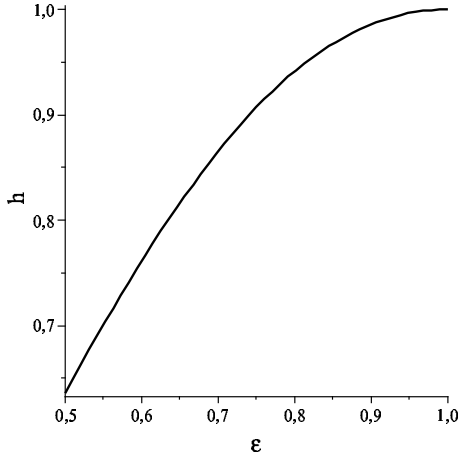
$$L = 4.2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \quad (4)$$

The question will be, whether experimental conditions can be prepared that allow to approach that described goal as shown in fig. 3. Thus, one of the most important tasks consists in preparing an intense circularly polarised photon beam.

### 2.2 Energy, intensity and polarisation of a photon beam

#### 2.2.1 Energy of the photon beam

The method considered could possibly cover a large range of antiproton energies up into the GeV/c region. In order to define the range of energies two antiproton momenta are considered, 10 GeV/c and 300 MeV/c. For an antiproton beam with a momentum of 10 GeV/c the velocity in units of the velocity of light is  $\beta = 0.9956$  and



**Fig. 4.** Helicity transfer  $h$  as a function of  $\varepsilon = \frac{E_\gamma}{E_e}$ .

$\gamma = \sqrt{\frac{1}{1-\beta^2}} = 10.7046$ . The energy region close the pion production threshold,  $150 \leq E_\gamma^{\bar{p}\text{-system}}/\text{MeV} \leq 200$  is considered first. The photon energy in the laboratory system for 200 MeV photons in the rest system of the antiprotons amounts to  $E_\gamma^{\text{lab}} = \frac{E_\gamma^{\bar{p}\text{-system}}}{\gamma \cdot (1+\beta)} = 9.36 \text{ MeV}$ . Working in the first resonance region with photons of 310 MeV needs a photon source in the laboratory of  $E_\gamma^{\text{lab}} = 14.58 \text{ MeV}$ . The respective values are  $E_\gamma^{\text{lab}} = 146.03 \text{ MeV}$  for  $E_\gamma^{\bar{p}\text{-system}} = 200 \text{ MeV}$  and  $E_\gamma^{\text{lab}} = 226.43 \text{ MeV}$  for  $E_\gamma^{\bar{p}\text{-system}} = 310 \text{ MeV}$  for the case of antiproton momenta of 300 MeV/c in a storage ring. The method will be discussed for the 300 MeV/c case.

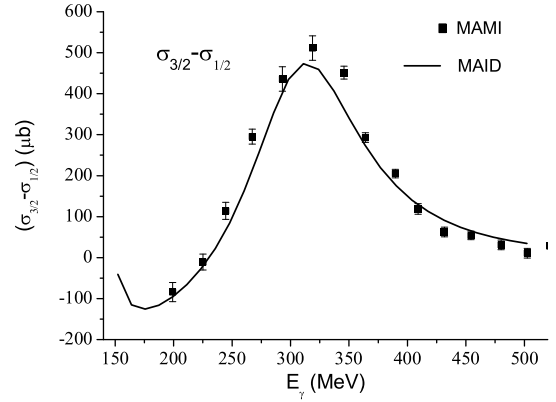
### 2.2.2 A suitable photon source

Electron bremsstrahlung provides the only powerful source for that  $\gamma$ -energy range. In the bremsstrahlung process, a helicity transfer from the electron to the photon takes place. An almost completely circularly polarised photon beam with the polarisation  $P_{\text{circ}}$ , close to the endpoint of the photon spectrum, can be prepared by a longitudinally polarised electron beam. Fig. 4 shows the degree of helicity transfer  $h$  [6] for a beam of bremsstrahlung with a 100% polarised electron beam as a function of  $\varepsilon = \frac{E_\gamma}{E_e}$ .

$$h = \frac{P_{\text{circ}}}{P_e} := \varepsilon \frac{\frac{4}{3} - \frac{1}{3}\varepsilon}{\frac{1}{3} + \frac{2}{3}\varepsilon + (1-\varepsilon)^2} \quad (5)$$

## 3 A closer look to the absorption cross sections and polarised electron sources

The applicability of the method depends on the knowledge of the input data, such as total absorption cross sections,  $\sigma_{1/2}$  and  $\sigma_{3/2}$ . However, other issues will be decisive for



**Fig. 5.** Data and results of calculations with the MAID program for the difference  $\sigma_{3/2} - \sigma_{1/2}$ .

efficient applications such as high luminosities. In addition, each implementation of such a method depends on the beam optics of the storage ring for a beam of polarised antiprotons and needs a cooled beam. Each energy regime needs special considerations. A new facility FAIR [7] will be built at GSI in Darmstadt, Germany. A storage ring, HESR, will be able to store  $10^{10} - 10^{11}$  antiprotons in the energy regime  $3 \leq E_p/\text{GeV} \leq 14$ . It is anticipated that  $N_{\bar{p}} = 10^{10}$  is the number of antiprotons produced at FAIR in 15 min.  $N_{\bar{p}} = 10^{10}$  will be also the number of antiprotons in the low energy ring considered in the following discussion.

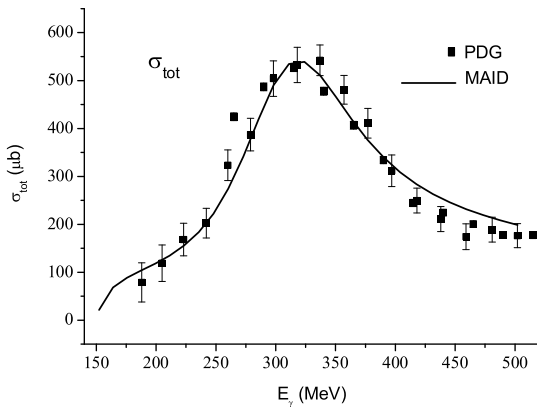
### 3.1 Experimental data for the total photon proton cross sections

In the last few years the cross section difference ( $\sigma_{3/2} - \sigma_{1/2}$ ) on the proton was measured in the photon energy range  $200 \leq E_\gamma/\text{MeV} \leq 2800$  at the accelerators MAMI, Mainz [8], and ELSA, Bonn [9]. From the total absorption cross section  $\sigma_{\text{tot}}$ , compiled by the particle data group [10], and the cross section difference ( $\sigma_{3/2} - \sigma_{1/2}$ ) the cross sections for circularly polarised photons,  $\sigma_{3/2}$  and  $\sigma_{1/2}$ , can be extracted:

$$\sigma_{3/2} = \sigma_{\text{tot}} + \frac{(\sigma_{3/2} - \sigma_{1/2})}{2} \quad (6)$$

$$\sigma_{1/2} = \sigma_{\text{tot}} - \frac{(\sigma_{3/2} - \sigma_{1/2})}{2} \quad (7)$$

Photoproduction data have been analyzed and described by the results of calculations based on a phenomenological model. The results of calculations with the computer program MAID [3] are shown together with the data in fig(s). 5 and 6. For the purpose of this paper the agreement between the MAID results and the measurements are good enough in order to use the MAID results for the polarised photon cross sections  $\sigma_{1/2}$  and  $\sigma_{3/2}$ , see fig. 2. The MAID results allow also to cover the near pion threshold region, not covered by the mentioned experiments.



**Fig. 6.** Data and results of calculations with the MAID program for the total absorption cross section.

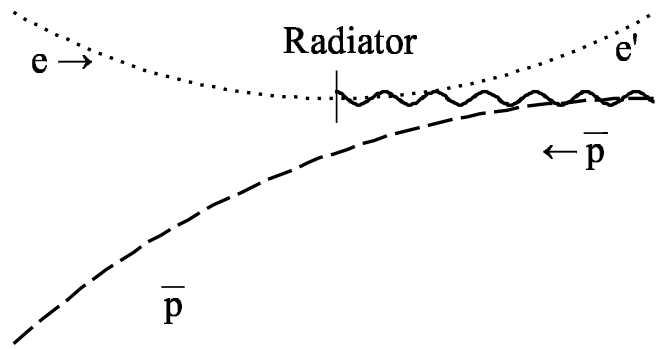
### 3.2 Polarised electrons

Polarised electrons are routinely produced via photo emission from GaAs-crystals either in pulsed or dc mode by LASER light, *e.g.* ref. [11] and ref. [12], respectively. Average currents of  $I_e = 200 \mu A$  with a beam polarisation of  $P_e = 0.85$  are achieved. The emittances reached are well adapted to use them for interactions with cooled hadron beams. On several places research is going on to increase the current. At Jefferson Lab. *e.g.* a dc polarized electron beam with a current of 1 mA has been produced recently.

## 4 Practical considerations

### 4.1 A possible implementation of a set-up

Antiprotons are stored in a 300 MeV/c storage ring equipped with cooling equipment and a Siberian Snake. The circumference of the ring is chosen to be 150 m. There is no need for specially large acceptances for the antiproton ring. The number of stored antiprotons,  $N_{\bar{p}} = 10^{10}$ , is assumed to be evenly distributed over the circumference of the ring. The ring has a straight section in order to install an interaction zone for the bremsstrahlung beam, see fig.7. The electron and antiproton beam enter into a strong magnetic field  $B$  (*e.g.* 3 T), perpendicular to their trajectories. The electron beam is fed in the vertical direction from above approaching the trajectory of the antiproton beam, see fig.7. Thereby, the electron beam gets bent upwards in vertical direction, the antiprotons are bent downwards. A radiator is inserted into the electron beam line at the point where the electron beam touches the field free trajectory of the antiproton beam. After the radiator the electron beam will be bent upwards towards a beam dump. The antiproton beam gets hit at the entrance into the magnetic field by the bremsstrahl beam. The beam diameter of the antiproton beam is chosen to be  $50 \mu m$ . In order to get a large overlap of the antiproton and  $\gamma$ -beam a focus of around  $30 \mu m$  in diameter of the electron beam on



**Fig. 7.** Schematic picture of the interaction zone between the bremsstrahl beam and the antiproton beam. The interaction takes place in the vertical direction.

the radiator should be accomplished. The beam entrance of the antiproton beam into the magnetic field and the end of the radiator are 10 mm apart. The distance of the electron beam to that entrance point adds up to  $230 \mu m$ . The antiproton beam passes the radiator at a distance of around  $150 \mu m$ . The characteristic bremsstrahl angle, without multiple scattering, leads to a distance of  $25 \mu m$  at the entrance point of the antiprotons into the magnetic field. That whole scheme is not optimized at all. It should demonstrate that it is possible to prepare a bremsstrahl beam and keeping the electron and antiproton beam separate. *E.g.* by increasing the the magnetic field by a factor of two and decreasing the momentum of the antiprotons by a factor of two the critical distances mentioned above reach the scale of 0.5 mm.

### 4.2 The number of photons and the luminosity

$N_\gamma$ , the number of polarised photons hitting the antiprotons, is the last number missing in order to calculate the luminosity. The relation

$$\frac{dN_\gamma}{dE_\gamma^{\bar{p}\text{-system}}} = N_e \frac{\Lambda}{E_\gamma^{\bar{p}\text{-system}}} \quad (8)$$

with  $\Lambda$  as the fraction of the radiation length of the radiator, allows to calculate  $N_\gamma$  with an adequate accuracy:  $N_\gamma = 2.8 \cdot 10^{13} s^{-1}$  with  $\Lambda = 0.06$  and  $N_e = 1.2 \cdot 10^{15} s^{-1}$ , corresponding to a  $200 \mu A$  beam current. The integration range  $155 \leq E_\gamma/MeV \leq 230$  covers the region of  $\sigma_{1/2}$  dominance of the total absorption cross section. The luminosity can be written as:

$$L = \frac{N_{\bar{p}} \cdot N_\gamma}{4\pi \cdot \sigma_{\bar{p}} \cdot \sigma_\gamma} \cdot \nu_b (cm^{-2}/s) \quad (9)$$

where  $\sigma_{\bar{p}}$  and  $\sigma_\gamma$  characterize the Gaussian transverse beam profiles. The diameters of the beams have been chosen, as discussed above, to  $d=50 \mu m$ , and the frequency of the bunch crossing is determined by the length of the antiproton storage ring and the velocity of the antiprotons. With those numbers the luminosity adds up to:  $L =$

$4.3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ . That result is almost identical with the result of eq. 3. The uncertainties entering as discussed above, mainly due to the chosen geometry in the interaction zone, may add up to a factor of three to five. The value of  $A = 0.06$  has been used routinely at Jefferson Lab. for carrying out photon induced reactions. An explicit calculation with the bremsstrahl spectrum, the degree of polarisation of electron beam of 85%, the unpolarized contribution due to the not complete helicity transfer, see fig.4, leads to a reduction of the figure-of-merit (FOM). That reduction depends on which photon energy range will be covered. Selecting the threshold region,  $E_{\text{threshold}} < E_{\gamma}/\text{MeV} \leq 185$ , the figure-of-merit reaches 0.18. Choosing,  $E_{\text{threshold}} < E_{\gamma}/\text{MeV} \leq 230$ , the region where  $\sigma_{1/2} \geq \sigma_{3/2}$ , FOM adds up to 0.075.

## 5 Preparation of an antineutron beam

For the  $\gamma$ -energy region  $E_{\text{threshold}} < E_{\gamma}^{\bar{p}\text{-system}}/\text{MeV} \leq 230$  the range of transverse momenta of the photoproduced antineutrons covers a momentum range of  $0 < p_{\bar{n}}^{\text{transverse}} \text{ MeV}/c \leq 125$  independently of the momenta of the antiprotons. Accordingly, it is much more favourable to prepare an antineutron beam using high energy storage rings for the antiprotons due to kinematical focusing. However, looking at fig.7 it might not be possible to reach high energies because of keeping the electron and antiproton beam separate. For the case of a 10 GeV/c antiprotons, certainly, the antiproton beam stays almost on his field free trajectory. That means the radiator has to be taken out of the free field position and positioned above it. The very low electron energy of only 10 MeV may still allow to find a configuration that crossing of the bremsstrahlung with the antiprotons becomes possible without interference of the electron and antiproton beam. In such a case a preparation of an antineutron beam with high polarisation can be prepared. The intensities would be limited by the production rate of antiprotons.

## 6 Summary

In sect. 2 a method has been identified that could have the potential to prepare a polarised antiproton beam in a storage ring. By making use of two largely different photon absorption cross sections,  $\sigma_{1/2}$  and  $\sigma_{3/2}$ , one of the antiproton spin projection gets enriched during the absorption processes and thus leads to a polarised antiproton beam. A suitable circularly polarised photon beam can be prepared by using a bremsstrahlung beam.

In addition, that method allows to extract from the stored antiprotons in the ring, via the reaction  $\vec{\gamma} + \vec{p} \rightarrow \pi^{-} + \vec{\bar{n}}$  a beam of polarised antineutrons.

That method allows also, by switching the polarisation of the electron, a measurement of the polarisation of the stored antiproton beam to a high degree of precision by detecting the produced antineutrons.

The advantage to use real photons resides in the fact that

one needs no large acceptance antiproton ring for the antiprotons. At this point it is not clear, how far in energy of the antiprotons the method is applicable. At an antiproton energy of 10 GeV/c *e.g.* the trajectory of the antiproton is almost a straight line. However, the electron energy decreases down to 10 MeV, which, possibly, allows a very close side way distance of the radiator to the antiproton beam.

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