The survival rate of anions inside Penning-Malmberg traps

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Abstract

The behaviour of anions inside Penning-Malmberg traps was investigated for application in forming antiprotonic atoms in the AEgIS experiment. It was found that field detachment due to the trapping potential is unlikely to occur. Cooling interactions with electrons will occur below the energy threshold for detachment, however, interactions with cold antiprotons could promote detachment, although analysis is limited by the available data. The Coulombic cooling between species can be modelled using a stopping-power formulation that has been developed. This is extended to consider detachment interactions, as well as a heavy particle as the cooling species.

1 Introduction

1.1 AEgIS experimental overview

The AEgIS (Antimatter experiment: Gravity, Interferometry, Spectroscopy) apparatus has been designed as a versatile experiment to investigate properties of antimatter and antimatter-matter bound systems. It receives an order of keV-energy beam of antiprotons from the Extra Low Energy Antiproton ring (ELENA). The antiprotons are confined using a Penning-Malmberg trap (described in Sec. 1.2). These antiprotons are further cooled, to increase the cross section for the synthesis of atomic systems such as anti-hydrogen or antiprotonic atoms.

Antiprotonic atoms are atomic systems containing a bound antiproton orbiting close to the atomic nucleus [1]. They are often formed in highly excited Rydberg states. For example antiprotonic helium is often formed in the N=38 state following its capture at large distances from the nucleus. Over a short timescale, the antiproton cascades down to lower-lying shells. This releases energy that causes outer electrons to be ejected, via the Auger process. When then antiproton reaches lower-energy states, it interacts the edge of the nucleus, and will annihilate with one of the outer nucleons [2]. Although the nucleus can further fragment, this process can create a highly-charged ion (HCI) with one less nucleon than the original species. These HCIs are separated and analysed using time of flight (TOF) spectroscopy. The ratio of the number of fragments that are missing a single proton or neutron is indicative of the prevalence of these nucleons on the surface of the nucleus [3]. For larger atoms, the number of neutrons is greater than the number of protons, thus the atom has a neutron skin. Neutron matter is poorly understood, and the skin thickness is ill-constrained by experiments. In this way, heavy atoms provide a valuable analog to neutron stars, energetic astrophysical objects that are some of the most extreme environments in the universe.

1.2 Penning-Malmberg traps

The central component of the AEgIS experiment consists of several Penning-Malmberg traps, which are capable of trapping ions for the duration of the experiment. These traps are comprised of a series of electrodes, ranging in potential from 200 V to 14 kV. The constructed potential is used to axially confine the beam — charged particles will be repulsed, and oscillate in the potential well. Moving charged particles experience a centripetal force in a magnetic field. The 1 and 5 T magnets used in the experiment at strong enough to confine the ions radially to prevent them from interacting with the walls, or escaping the trap.

1.3 Anions

Negatively charged atoms, anions, have prospective applications within several contexts for the AEgIS experiment. Cold anions are required to synthesise antiprotonic atoms by charge-exchange interactions, as proposed in [4]. There are two developed ion sources for potential use in this system. One uses a gas mixture to produce a range of anions [5], including H^- and C_2^-. The other produces I^- anions. In both cases, the anions are produced with energy in the order of keV, while for use in the experiment they are required to be in the order of an electron volt. The intended method achieves this through mixing with cold electrons or antiprotons. As the species have the same charge, they will repulse each other, and the anions will transfer momentum to the cooling species. The process of cooling and utilising the anions requires trapping and retaining them in a volatile environment. Penning-Malmberg traps are restricted in efficacy to charged particles: if the additional electron is detached, the neutral atom will be lost from the trap.

The energy required to neutralise an anion from a singly negative state is defined as the electron affinity (EA), which can be used as a measure of the stability of the anion. Table 1 compares the EAs of different anions that are candidates for injection in the next stages of AEgIS.

Species	Electron affinity (eV)
H	0.755
C_2	3.273
I	3.059

Table 1: Electron affinities for possible anion species for injection into the AEgIS experiment.

There are several detachment mechanisms that need to be considered through the injection, mixing and cooling procedures. These include field ionisation, and detachment due to collisions with other anions, electrons, and antiprotons. Analysis of the likelihood of these events will work towards constraining the statistics of the experiment, and help to determine the optimal species choice to maximise the survival of the anions.

2 Analysis of detachment mechanisms

In the following section, several detachment mechanisms are investigated to estimate the likelihood of their significant impact on the survival of anions through the course of the experiment. For all mechanisms there is a scarcity of experimental data for the relevant anions. As such, all previously reported results are presented, and analysed with consideration for their electron affinity and mass.

2.1 Field ionisation

The high-voltage (−14 kV) electrodes with the Penning-Malmberg traps create a sharp electron field gradient (14 kV/cm) that the anions interact with as they reflect off the potential. As this field overlaps with the anion, the potential that binds the additional electron to the nuclei becomes narrow, and in principal, could allow the electron to tunnel away from the electron field gradient and the nucleus, neutralising the atom.

Fabrikant [6] investigated field detachment of Rb^-, an anion with an electron affinity of 0.486 eV. This species is less tightly bound than all those being considered for injection, so can be viewed as an upper bound on detachment likelihood. They calculated the decay (detachment) probability per atomic time, varying the electric-field gradient from 1 to 4 MV/cm. Their results are reproduced in Fig. 1. The value falls several orders of magnitude as the gradient decreases for 2 to 1 MeV/cm, to a minimum of 10^{-12} a.u.. The exponential trend present in the lower-field section can be extrapolated down to 14 kV/cm, to find a decay probability per atomic time of the order of 10^{-22} a.u. .

Additionally, photodetachment experiments are often performed with strong electric field gradients. Du and Delos [7] employed a field of a "few hundred of kV/cm" for their investigation of the photodetachment cross section of H^-. This shows that the electric field itself will not cause detachment.

2.2 Impact detachment

2.2.1 Change of frame

Within the AEgIS experiment, anions are ejected from an ion source into the Penning-Malmberg trap containing cold electrons and/or antiprotons. Typically, cross sections are presented in terms of collision energy of a projectile with respect to a stationary anion. To analyse these cross sections in the context of AEgIS with reverse kinematics, the kinetic energy of the anion must be transformed to the kinetic energy of the projectile, in a frame where the anion is stationary.

The change of frame is calculated by considering the energy of the anion, E_A, which can be used to calculate its velocity, v, by

$$v = \sqrt{\frac{2E_{\mathrm{A}}}{m_{\mathrm{A}}}}, \tag{1}$$

where m_A is the mass of the anion.

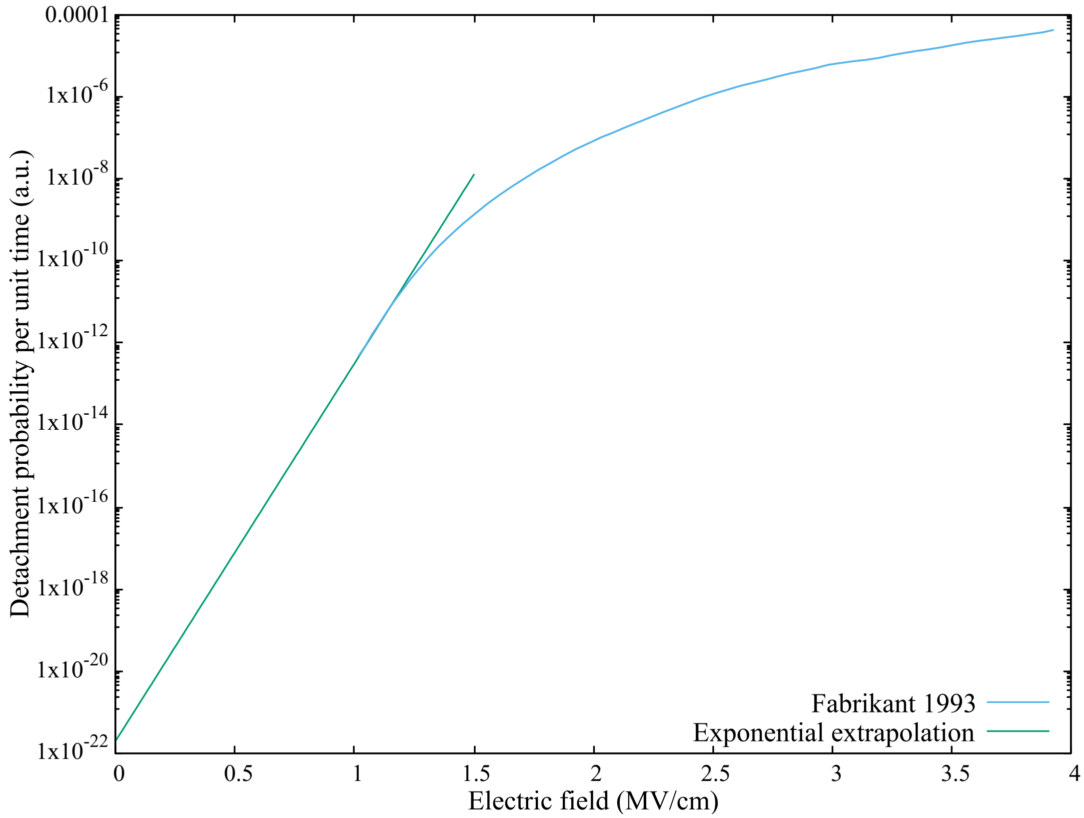

Figure 1: Probability of detachment per atomic time for Rb^- anions in various electric fields. An exponential fit of $2 \times 10^{-22} e^{21.172x}$ extends the trend to the electric field strength of concern.

When changing frames, the velocity of the anion becomes the velocity of the cooling species, from which its kinetic energy, E_c, can be calculated by

$$E_c = \frac{1}{2} m_c v^2. \tag{2}$$

Equations (1) and (2) can be combined as

$$E_c = E_A \frac{m_c}{m_A}. \tag{3}$$

Due to the mass difference between the anion and cooling species, the collision energy after changing frames is significantly smaller than the kinetic energy of the anion as it is typically presented. Table 2 presents impact energies, in the rest frame of the anion, where it has 2 keV of kinetic energy in the lab frame.

Anion species	Electron energy (eV)	Antiproton energy (eV)
H^-	1.09	2.00×10^3
C_2^-	4.54×10^{-2}	8.33×10^1
I^-	8.58×10^{-3}	1.57×10^1

Table 2: Frame-shifted collision energy for cooling reactions in the anions rest frame, for an anion lab energy of 2 keV.

2.2.2 Collisions with electrons

Detachment interactions for collisions between electrons and anions have been investigated for several atomic and molecular anions. Fig. 2 presents the electron-impact detachment cross sections for collisions with H^- [8, 9], C^- [10], O^- [10, 11], F^- [12], B_2^- [13], C_2^- [13], and F_2^- [14]. It is clear that the detachment cross section rises quickly once the collision energy exceeds some threshold.

The threshold energies, E_{th}, for electron-impact detachment, can be approximated as $E_{th} = 2.2E_{EA} + 0.27$ [13], where E_{EA} is the electron affinity. These energies are reported Tab. 3 for the anions of concern. As all thresholds are greater than the collision energies reported in Tab. 2, one can be confident that any detachment will be negligible.

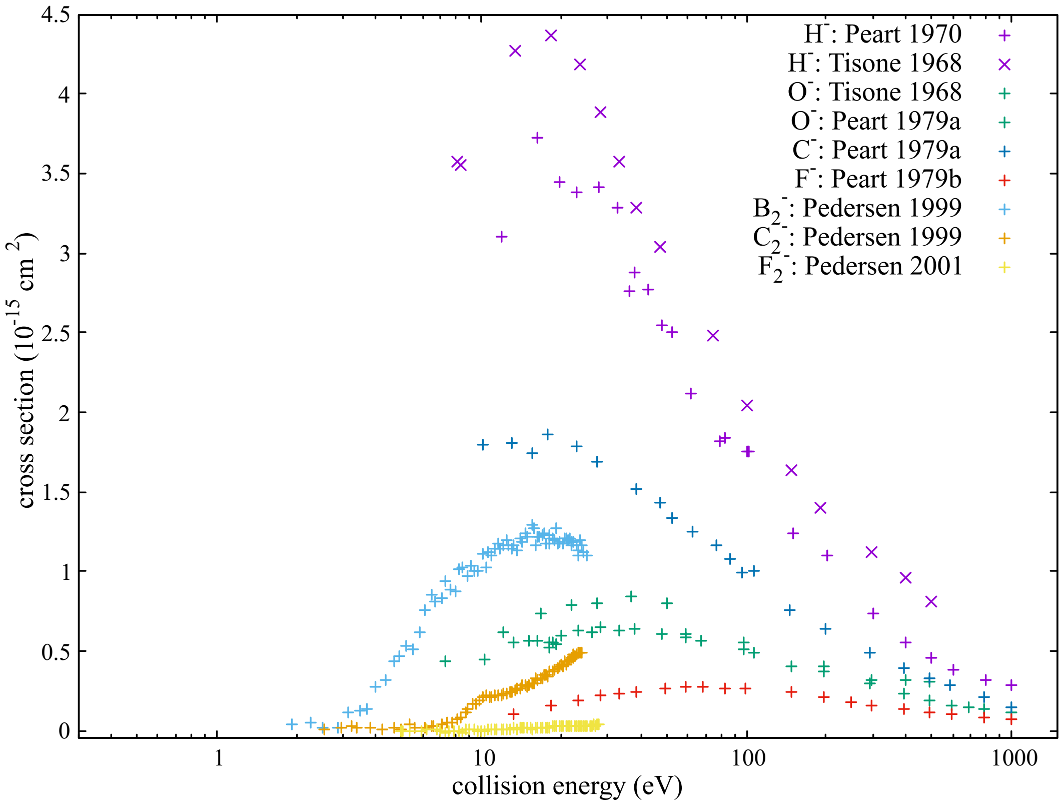

Figure 2: Electron-impact detachment cross sections for several anions [8, 9, 10, 12, 11, 13, 14]. All collision energies are given with reference to a stationary anion.

Species	Threshold energy (eV)
H^-	1.93
C_2^-	7.47
I^-	7.00

Table 3: Electron-impact detachment threshold for anion species relevant to AEgIS. Threshold is calculated as $E_{\mathrm{th}} = 2.2E_{\mathrm{EA}} + 0.27$ [13].

Also of relevance in collisions with molecular species is the process of dissociation, where the atoms break apart. The only molecular anion considered for use is AEgIS is C_2^-, which has an experimental dissociation threshold of approximately 12 eV [13]. As this is significantly larger than the threshold for detachment, these channels are not of consequence.

2.2.3 Collisions with antiprotons

In contrast with the electron-projectile case, the characteristics of antiproton collisions with anions are not effectively constrained by experiential and theoretical data.

Theoretical electron-detachment cross sections for antiproton collisions with H^-, calculated by Igarashi *et al.* [15], who used a close-coupling (CC) method, and Cohen and Fiorentini [16] and Cohen [17], who used a classical-trajectory Monte Calo (CTMC) method. Their results, into the rest frame of the anion, are presented in Fig. 3.

The cross section in the region of interest, at 2 keV for the H^- anion, is in the range of 3–8$\times 10^{-15}$ cm^2. This indicates that it will be necessary to consider detachment when considering cooling processes with antiprotons. The CC and CTMC methods produce diverging results, particularly at low collision energies. More collision data is required to constrain the cross section beyond an order-of-magnitude estimate.

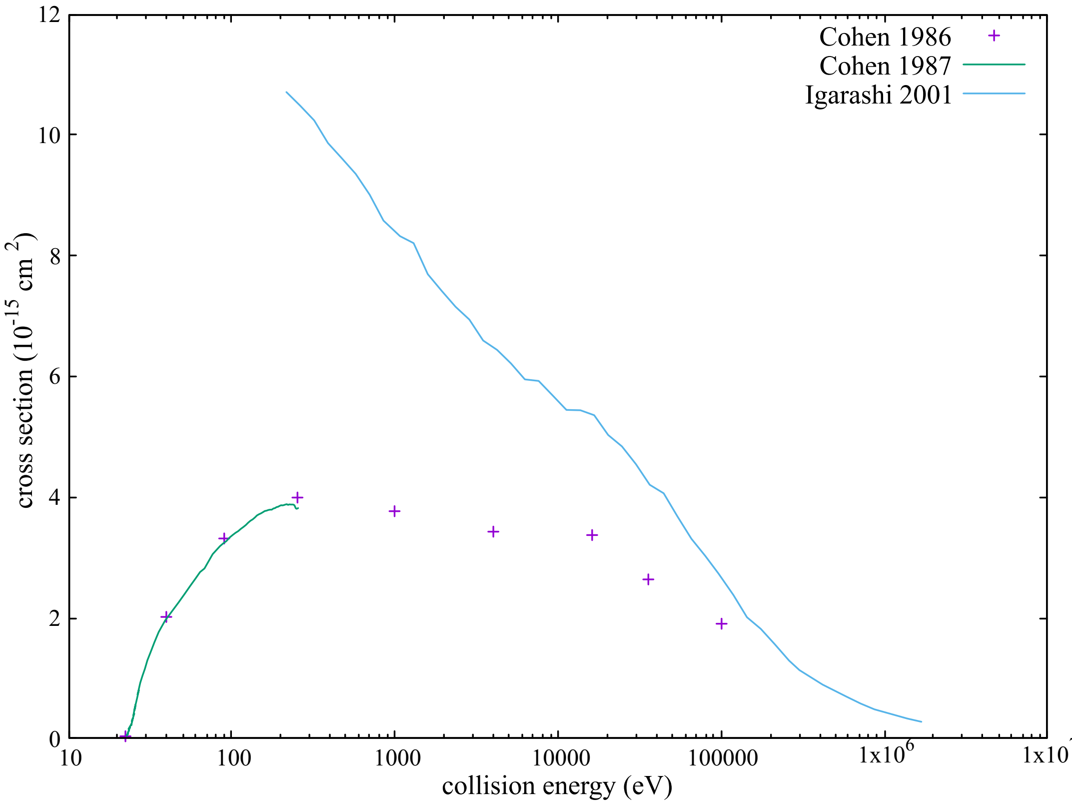

Figure 3: Antiproton-impact detachment cross sections for collisions with H^- anions [15, 16, 17]. All collision energies are given with reference to a stationary anion.

3 Repulsive Cooling

3.1 Conserved particles case

In the classical approximation, the Coulomb cooling between two species can be modelled using a set of differential equations. Rolston and Gabrielse [18] investigated electron cooling of antiprotons. They describe the time constant, the time taken to reach equilibrium, as

$$\tau_c = \frac{3m_\mathrm{p}m_\mathrm{e}c^3}{8\sqrt{2\pi}n_\mathrm{e}e^4\ln\Lambda}\left(\frac{k_\mathrm{B}T_\mathrm{p}}{m_\mathrm{p}c^2}+\frac{k_\mathrm{B}T_\mathrm{e}}{m_\mathrm{e}c^2}\right)^{3/2}, \tag{4}$$

where m_p and m_e, are the masses of the proton and electron, and T_p and T_e are their temperatures. The number density of the electrons is n_e, and Λ is the ratio between the Debye length and minimum impact parameter considered. This factor arises from the necessary cutoff in stopping power calculations, to prevent divergence of the integral [19], and can be written as

$$\Lambda = 4\times10^3\sqrt{\frac{T_\mathrm{e}}{n_\mathrm{e}}}\left(T_\mathrm{e}+\frac{T_\mathrm{p}}{1836}+\frac{\sqrt{T_\mathrm{p}T_\mathrm{e}}}{21}\right). \tag{5}$$

These equation can be used in conjunction with the rate equations of

$$\frac{\mathrm{d}}{\mathrm{d}t}T_\mathrm{p} = -\frac{1}{\tau_c}(T_\mathrm{p}-T_\mathrm{e}) \tag{6}$$

and

$$\frac{\mathrm{d}}{\mathrm{d}t}T_\mathrm{e} = \frac{N_\mathrm{p}}{N_\mathrm{e}}\frac{1}{\tau_c}(T_\mathrm{p}-T_\mathrm{e})-\frac{1}{\tau_\mathrm{e}}(T_\mathrm{e}-T_0), \tag{7}$$

where N_p and N_e are the number of protons and electrons. In their formulation, the cooling constant for electrons, τ_e, was approximated to be 0.1 s, and the surrounding temperature, T_0, was set to 4.2 K.

This work was extended to the case of general hot cations by Bernard *et al.* [19], by considering the mass, m_{i}, and charge, Z, of the particles to be cooled. In this way the equations were generalised to

$$\tau_c = \frac{3m_{\mathrm{i}}m_{\mathrm{e}}c^3}{8\sqrt{2\pi}n_{\mathrm{e}}Z^2e^4\ln\Lambda}\left(\frac{k_{\mathrm{B}}T_{\mathrm{i}}}{m_{\mathrm{i}}c^2}+\frac{k_{\mathrm{B}}T_{\mathrm{e}}}{m_{\mathrm{e}}c^2}^{3/2}\right), \tag{8}$$

and

$$\Lambda = \frac{4\pi}{Z}\left(\frac{\epsilon_0 k_{\mathrm{B}}}{e^2}\right)^{3/2}\sqrt{\frac{T_{\mathrm{e}}}{n_{\mathrm{e}}}}\left(T_{\mathrm{e}}+\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}T_{\mathrm{i}}+2\sqrt{\frac{T_{\mathrm{i}}T_{\mathrm{e}}m_{\mathrm{e}}}{m_{\mathrm{i}}}}\right). \tag{9}$$

Additionally, they presented a more general expression for the cooling time of the electron, as

$$\tau_{\mathrm{e}} = \frac{3m_{\mathrm{e}}^3c^3}{4Z^4e^4B^2}, \tag{10}$$

where B is the magnetic field strength.

An alternate set of equations in given in Kojima *et al.* [20], who presented the same generalisation with different multiplicative constants, as

$$\tau_c = \frac{3\sqrt{2\pi^3}\epsilon_0^2 m_{\mathrm{i}}m_{\mathrm{e}}c^3}{n_{\mathrm{e}}Z^2e^4\ln\Lambda}\left(\frac{k_{\mathrm{B}}T_{\mathrm{i}}}{m_{\mathrm{i}}c^2}+\frac{k_{\mathrm{B}}T_{\mathrm{e}}}{m_{\mathrm{e}}c^2}\right)^{3/2}, \tag{11}$$

and

$$\Lambda = \frac{4\pi}{Z}\left(\frac{\epsilon_0 k_{\mathrm{B}}}{e^2}\right)^{3/2}\sqrt{\frac{T_{\mathrm{e}}}{n_{\mathrm{e}}}}\left(T_{\mathrm{e}}+\frac{m_{\mathrm{e}}}{m_{\mathrm{i}}}T_{\mathrm{i}}+2\sqrt{\frac{T_{\mathrm{i}}T_{\mathrm{e}}m_{\mathrm{e}}}{m_{\mathrm{i}}}}\right). \tag{12}$$

It is currently unclear whose formulation of the system (Eqs. (8) and (9), or (11) and (12)) is correct, or if the discrepancy can be accounted for by a difference in unit conventions. It is worth mentioning that the work of Bernard *et al.* [19] has been published in a peer-reviewed journal and provides deeper explanation for the equations, and Kojima *et al.* [20] was sourced from an internal review document in personal communications.

The formulation could be further generalised to characterise interactions with cold antiprotons, by exchanging its mass with the mass of the electron. As the antiprotons are too heavy to experience significant synchrotron cooling in the 5 T magnetic field, it is expected that the cooling will occur at a higher rate, but only to a warmer asymptotic temperature.

3.2 Allowing for detachment

For cooling interactions where detachment interactions are non-negligible, the number of anions present would decrease as time progresses, as they become neutral and are lost from the trap. Additionally, in processes where an electron is ejected from the atom, it preferentially has minimal energy, for impact with both light [21] and heavy projectiles [22]. Consequentially, it is likely that the detached electron will remain in the trap, and cool by synchrotron radiation to equilibrium with the other trapped electrons.

When accounting for detachment, both the decrease in anions and increase in electrons must be accounted for. In this model, it is assumed that the electrons instantaneously cool to the temperature of the cold electrons. Although this could be better approximated by a second set of cooling equations, the difference in time would be negligible for configurations with a large magnetic field.

To this end, the number of detachment interactions that occur in a given time interval, N_d, must be calculated. For this, the detachment cross section is required. Kojima *et al.* [20] describe the occurrence rate for a process in an ion trap as

$$\begin{aligned}\frac{\mathrm{d}N_{\mathrm{i}}}{\mathrm{d}t} &= -\sigma(E_{\mathrm{i}})v_{\mathrm{i}}n_{\mathrm{e}}N_{\mathrm{i}}\\ &= -\sigma(E_{\mathrm{i}})\sqrt{\frac{2E_{\mathrm{i}}}{m}}n_{\mathrm{e}}N_{\mathrm{i}}.\end{aligned} \tag{13}$$

Hence, the number of ions that are lost — and the number of electron gained — at each time-step is

$$N_{\mathrm{loss}} = -\sigma(E_{\mathrm{i}})\sqrt{\frac{2E_{\mathrm{i}}}{m}}n_{\mathrm{e}}N_{\mathrm{i}}\Delta t. \tag{14}$$

It may be more convenient to express the loss rate in terms of temperature, as

$$N_{\mathrm{loss}} = -\sigma(k_{\mathrm{B}}T_{\mathrm{i}})\sqrt{\frac{2k_{\mathrm{B}}T_{\mathrm{i}}}{m}}n_{\mathrm{e}}N_{\mathrm{i}}\Delta t. \tag{15}$$

This can be incorporated into Eqs. (6) and (7), by evaluating N_{p} and N_{e} as functions of time.

4 Conclusion and outlook

The likelihood for detachment to occur in anion collisions with electron or antiprotons was investigated, for the purpose of characterising the survival rate of anions in the AEgIS Penning-Malmberg trap. It was found that by accounting for the relative difference in collision energy, a 2 keV anion would fall below the detachment threshold when interacting with cold electrons. In collisions with antiprotons, the cross section is likely to be near its maximum, however the available theoretical data is not sufficient to draw conclusions regarding its value. Further work could analyse the likelihood of detachment in interactions within the anion cloud, or with the residual or carrier gas.

Preliminary investigation into calculating the cooling times for electron or antiproton mixing with anions shows promise. The equations must be solved numerically, and thoroughly tested before results can be obtained. In the extension to cold antiprotons, the antiproton-impact detachment cross section is required, which is currently not well characterised.

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