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Antiproton annihilation in very low-energy antihydrogen scattering by simple atoms and molecules

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Abstract

The aim of experimentalists currently working on the preparation of antihydrogen is to trap it at very low temperatures so that its properties can be studied. Of concern to experimentalists are processes that lead to a loss of antihydrogen through annihilation. The dominant annihilation process that leads to the loss of antihydrogen is the annihilation of the antiproton with nuclei through the strong interaction.

A recent scattering calculation of antihydrogen with hydrogen at very low energy, using the complex strong interaction potential of Kohno and Weise, has found an average annihilation cross-section of $0.13E^{-1/2}a_0^{-2}$, where E is the energy of relative motion.

The antihydrogen–helium system is of particular interest to experimentalists as helium may be present as an impurity in the trap. Also there is interest in the possibility of using it to cool antihydrogen. We present a treatment of antihydrogen scattering with helium at very low temperatures. The annihilation cross-sections obtained are much larger than antihydrogen–hydrogen scattering cross-section, making it very unlikely that helium can be used to cool antihydrogen.

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1. Introduction

The ATHENA and ATRAP projects are continuing their work on antihydrogen ($\overline{\mathrm{H}}$) at CERN after their successful preparation of $\overline{\mathrm{H}}$ in 2002. See for example [1,2]. However, it still remains to trap and store cold $\overline{\mathrm{H}}$ at very low temperatures so that its properties can be examined. This will make possible tests of CPT invariance of quantum field theory and the equivalence principle of general relativity.

Antihydrogen is currently detected via its annihilation products: 2 gamma rays from the positron annihilation and mesons from the antiproton annihilation. In quantum field theory the magnitude of the cross-section for annihilation is directly proportional to the coupling constant.

The annihilation of the positron is brought about by the electromagnetic interaction and the coupling constant in quantum electrodynamics is the fine structure constant 1/137. Annihilation of the antiproton is due to the strong interaction. The fundamental theory of the strong interaction is quantum chromodynamics (QCD), and at the low energies being considered, the coupling constant is ~1. A description of nuclear interactions from QCD is yet to be developed. Annihilation occurs when the nuclear distributions begin to overlap and colour-gluon dynamics are important. We can expect the annihilation cross-section of the antiproton to be much larger than for the positron annihilation.

Of course, annihilation necessarily follows a rearrangement process such as the formation of protonium ($\mathrm{p}\bar{\mathrm{p}}$) and positronium in $\mathrm{H}\overline{\mathrm{H}}$ scattering, but in this case the loss

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Table 1
Comparison values at $k = 0.0004$ a.u.

	Elastic cross-section (a_0^{-2})		Average[a] annihilation cross-section ($E^{-1/2}a_0^{-2}$)
	Average[a] including the strong interaction	Average[a] percentage increase over the value without the strong interaction	
Our results	908	15	0.13
Jonsell et al.	890	16[b]	0.15

[a] $\frac{3}{4}$(triplet value) + $\frac{1}{4}$(singlet value).

[b] Jonsell et al. obtained a slightly lower value for the elastic cross-section without the strong interaction.

rate of $\mathrm{H}\overline{\mathrm{H}}$ is determined by the cross-section for the rearrangement process. QCD is non-perturbative at low energies and there is no obvious preferred channel for annihilation to occur. It is for determining the rate of $\overline{\mathrm{H}}$ loss in *annihilation in flight*, i.e. annihilation in what would otherwise be the elastic channel, that an accurate quantum mechanical description of the annihilation process itself is required.

For the purpose of calculating annihilation cross-sections, optical potentials are used. Although optical potentials are phenomenological they have been shown to reproduce experimental results accurately.

We have recently carried out a treatment [3] of very low-energy antihydrogen–hydrogen $\mathrm{H}\overline{\mathrm{H}}$ scattering using the complex potential of Kohno and Weise [4]. The potential allows for the isotopic spin invariance of the strong interaction and for the spin state of the nuclei. Antiproton annihilation is brought about by a pure imaginary optical potential of Woods–Saxon form.

The Born–Oppenheimer potential used for the electromagnetic interaction was pure coulombic at internuclear distances less than $0.8a_0$ and behaved asymptotically like a Van der Waals potential.

The results we obtain for the annihilation cross-section and the change in elastic cross-section are similar to those obtained by Jonsell et al. [5], using the effective range method of Trueman [6]. They are significantly smaller than the values obtained by Voronin and Carbonell [7] using a coupled channel method and a complex strong interaction potential. A comparison between our results and those obtained by Jonsell et al. is given in Table 1.

In this paper, we turn our attention to the $\overline{\mathrm{H}}$ scattering with helium and calculate the antiproton annihilation cross section and the change of the elastic cross-section due to the inclusion of the strong interaction. We find that the annihilation cross-section is much larger than for $\overline{\mathrm{H}}\mathrm{H}$ scattering.

2. Antihydrogen–helium scattering at very low energies

The internuclear potential of helium–antihydrogen due to the lepton interaction and internuclear attraction has been calculated within the Born–Oppenheimer approximation by Strasburger and Chojnacki [8]. The potential at the whole range of r was calculated as $V_{\mathrm{BO}}(r) = E_{\mathrm{tot}}(r) - E_{\mathrm{He}} - E_{\overline{\mathrm{H}}}$ where nonrelativistic energies of helium and antihydrogen, $E_{\mathrm{He}} = -2.9031244$, $E_{\overline{\mathrm{H}}} = -0.5$.

In the region $0 < r < 12$, $E_{\mathrm{tot}}(r)$ is the sum of the numerical leptonic energy $\varepsilon^{i}_{\mathrm{lep}}(r)$, calculated at $i = 34$, r values by Strasburger and Chojnacki and the internuclear potential $-2/r$. The Born–Oppenheimer potential in this region is thus of the form

$$V_{\mathrm{BO}}(r) = -\frac{2}{r} + \varepsilon^{i}_{\mathrm{lep}}(r) - E_{\mathrm{He}} - E_{\overline{\mathrm{H}}}. \qquad (1)$$

The potential is interpolated in this region using a cubic spline. Beyond $r = 12$, the numerical potential is smoothly joined to the asymptotic form,

$$V(r) = \frac{C_6}{r^6} + \frac{C_8}{r^8} + \frac{C_{10}}{r^{10}}. \qquad (2)$$

The Born–Oppenheimer potential has been used in the calculation of elastic scattering and nuclear annihilation cross-sections [9], but only sparse data were available for small internuclear distances. Strasburger and Chojnacki have since solved the leptonic energy for a larger number of internuclear distances $i = 98$ [10]. The resulting energies are lower than in their previous calculation but this is not expected to be significant. The interaction energy has also been supplemented by an adiabatic correction which is significant at small internuclear distances.

Cross-section results for elastic s-wave scattering without the strong interaction, using the recent Born–Oppenheimer potential, are given in Table 2. The elastic cross-section is approximately constant in the energy range $10^{-10} \rightarrow 10^{-8}$ a.u., with an average value $9.43a_0^{-2}$.

The initial strong interaction potential used for $\mathrm{He}\overline{\mathrm{H}}$ scattering at low energies is that of Davies et al. [11]. It is an optical potential given by

Table 2
Elastic cross-section results without the inclusion of the strong interaction

Energy (a.u.)	Elastic cross-section (a_0^{-2})
10^{-10}	9.3203
5×10^{-9}	9.2568
10^{-9}	9.3316
5×10^{-8}	9.8562
10^{-8}	9.3925
10^{-7}	10.4645
10^{-6}	20.2676
5×10^{-4}	8.1138