Indication of the Wigner threshold law in collisions between antiprotonic helium and hydrogenic molecules

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The temperature dependence of the quenching cross section of the state $(39, 35)$ of antiprotonic helium in collisions with hydrogen and deuterium molecules has been measured. We found that the quenching cross section increases with decreasing temperature, in contradiction to the simple activation barrier model which could successfully describe the collisions in case of other antiprotonic states. The temperature (i.e. thermal velocity) dependence of the cross section roughly follows the $1/v$ Wigner threshold law of exothermic reactions involving neutral particles.

1 Introduction

The lifetimes of the metastable states of antiprotonic helium atoms ($\overline{\mathrm{p}}\mathrm{He}^+ \equiv \overline{\mathrm{p}} - \mathrm{e}^- - \mathrm{He}^{2+}$, characterized by the principal quantum number n and orbital quantum number l) decrease when $\overline{\mathrm{p}}\mathrm{He}^+$ atoms collide with H_2 or D_2 molecules [1, 2, 3]. This quenching phenomenon is particularly interesting because i) the quenching remains strong even below 30 K, ii) the quenching cross section σ_q strongly depends on the quantum numbers (n, l) of the $\overline{\text{p}}\text{He}^+$ atom [4, 5, 6], and iii) σ_q is usually a factor of ∼1.5 smaller for D_2 than for H_2 [7, 8].

From the physico-chemical point of view an antiprotonic helium atom can be thought of as an exotic hydrogen atom with a $[\overline{\text{p}}\text{He}^{2+}]_{(n,l)}$ 'nucleus' with an effective charge of ∼1.7 e. Around this an electron is bound in a $1s$ orbit with a binding energy of ∼25 eV. Thus by studying the $\overline{\text{p}}\text{He}^+ + \text{H}_2$ and $\overline{\text{p}}\text{He}^+ + \text{D}_2$ collisions we can obtain information on the reactions

$$[\overline{\text{p}}\text{He}^+]_{(n,l)} + \text{H}_2 \quad \rightarrow \quad [\text{He}^+\overline{\text{p}}\text{H}]^* + \text{H}, \tag{1}$$

$$[\overline{\text{p}}\text{He}^+]_{(n,l)} + \text{D}_2 \quad \rightarrow \quad [\text{He}^+\overline{\text{p}}\text{D}]^* + \text{D}, \tag{2}$$

which are the most probable reactions responsible for quenching. The above reactions are very similar to the most fundamental hydrogen exchange reactions such as $\text{D} + \text{H}_2 \rightarrow \text{DH} + \text{H}$, whose cross sections are not known at low temperatures. This is very unfortunate since similar low temperature reactions play an important role in e.g. cold interstellar and protostellar clouds. In case of antiprotonic helium, however, the formed complex 'molecule' is expected to be short-lived ($\tau \lesssim$ ns), therefore the reaction is immediately followed by the annihilation of the antiproton. By detecting these annihilations, we can measure the lifetime and consequently the quenching cross section of an antiprotonic state. The molecular complex is most likely deeply bound so the reactions are exothermic.

According to the theoretical calculations of Sauge and Valiron [9], an (n, l)-dependent activation barrier exists for the $\overline{\text{p}}\text{He}^+ + \text{H}_2$ and $\overline{\text{p}}\text{He}^+ + \text{D}_2$ collisions, which can qualitatively explain the observed (n, l) dependence of the quenching cross section σ_q. Based on the activation barrier model, the temperature (T) dependence of σ_q can be written as

$$\sigma_q = \sigma_0 \exp(-E_b/kT) + \sigma_t, \tag{3}$$

where the first term expresses an Arrhenius-type temperature dependence, while σ_t accounts for a temperature-independent tunnelling effect. Here E_b is the state-dependent barrier height, σ_0 is the cross section at infinitely high temperatures (pre-exponential cross section), and k is the Boltzmann constant.

We already measured σ_q of the antiprotonic states $(n, l) = (38, 37)$ and $(37, 34)$ at different temperatures, and concluded that the temperature dependence of σ_q does follow Eq. (3) in case of these two states [10]: at higher temperatures ($T \gtrsim 100$ K), the Arrhenius term dominates, and σ_q decreases with decreasing temperature. However, it levels off below ∼30 K, where σ_t is the dominating term. Now we made a detailed temperature scan of the state $(39, 35)$ as well. Previously, this state has only been studied at 30 K, where the quenching cross section was found to be close to the geometrical cross section, both with H_2 and D_2. This, and also the calculations of Sauge and Valiron, suggested that there is no activation barrier for the state $(39, 35)$ and thus all collisions should result in quenching. Since there is no activation barrier, Eq. (3) no longer holds and one might expect a temperature-independent (i.e. constant) quenching cross section.

2 Experimental setup and method

The experimental setup was practically identical to our previous measurements [10, 11, 12]. Antiprotonic helium atoms were created by stopping pulses of $\sim 3 \times 10^7$ antiprotons (arriving every ∼100 seconds) with an energy of 5.3 MeV in a cryogenic helium gas target. After slowing down by collisions with helium atoms, about 3% of the antiprotons are captured into various long-lived ($\tau \sim \mu$s) metastable states. The subsequent annihilation of the captured antiprotons (mainly into charged pions) could be observed in two adjacent Cherenkov counters, which were connected to two gateable fine-mesh photomultipliers. The outputs of the photomultipliers were recorded using a digital oscilloscope as an 'analog delayed annihilation time spectrum' which is essentially the annihilation rate of the antiprotons versus time. A dye laser pumped by a Nd:YAG laser was used to irradiate our helium target after each antiproton pulse. The gas target consisted of ^{4}He (purity: 99.9996%) to which hydrogen (purity: 99.999%) or deuterium (purity: 99.8%) was premixed at molar concentrations of 30 to 10000 ppm with a relative accuracy of 2%.

The quenching cross section of a metastable antiprotonic state can be obtained by measuring its decay rate γ at different admixture (hydrogen or deuterium) concentrations. Assuming that the antiprotonic helium atoms are quenched in binary collisions with the admixture molecules, γ can be expressed in terms of the state-dependent quenching cross section σ_q as

$$\gamma = \gamma_0 + n_{\mathrm{adm}}\, v_{\mathrm{th}}\, \sigma_q, \tag{4}$$

where γ_0 is the 'intrinsic' decay rate of the state in a collision-free environment (this is calculated theoretically), n_{adm} is the absolute number density of the admixture molecules, and $v_{\mathrm{th}} = \sqrt{8kT/(\pi M_{\mathrm{red}})}$ is the average relative thermal velocity, with M_{red} being the reduced mass of the colliding species [13]. To obtain the decay rate γ of a metastable state, we induced transitions between this state and a short-lived ($\tau \lesssim$ ns) state by a resonant laser pulse, and measured the antiproton population of the metastable state versus time. A detailed description of this so-called 't1-scan' method can be found in our previous publication [10].

3 Results and discussion

The left side of Fig. 1 shows the logarithm of the newly and previously [6, 7, 10] measured quenching cross sections of the state $(39, 35)$ versus the inverse temperature (Arrhenius plot). One can clearly see that σ_q increases with decreasing temperature, both with H_2 and D_2. This contradicts the naive assumption that it should be temperature-independent and close to the geometrical cross section. In fact, at the lowest temperature, the measured σ_q is almost twice as large as the geometrical cross section. The cross section of the state $(39, 35)$ does not follow Eq. (3) either. For comparison, the right side of Fig. 1 shows σ_q of the state $(38, 37)$ measured previously [6, 10], which does follow Eq. (3).

One process that might cause the increase of the quenching cross section of the state $(39, 35)$ at low temperatures is the following. Due to the lack of the activation barrier for the state $(39, 35)$, the potential between the $\overline{\mathrm{p}}\mathrm{He}^+$ atom and the colliding H_2/D_2 molecule is always attractive, therefore the H_2/D_2 molecule is attracted towards the $\overline{\mathrm{p}}\mathrm{He}^+$ atom even from a distance, which results in an increased cross section. At lower temperatures, the velocity of the colliding species is lower, therefore this 'capture' process is enhanced.

Figure 2 shows the quenching cross section of the state $(39, 35)$ with D_2 as a function of the inverse collisional velocity $1/v_{\mathrm{th}}$. The data points are quite well aligned on a straight

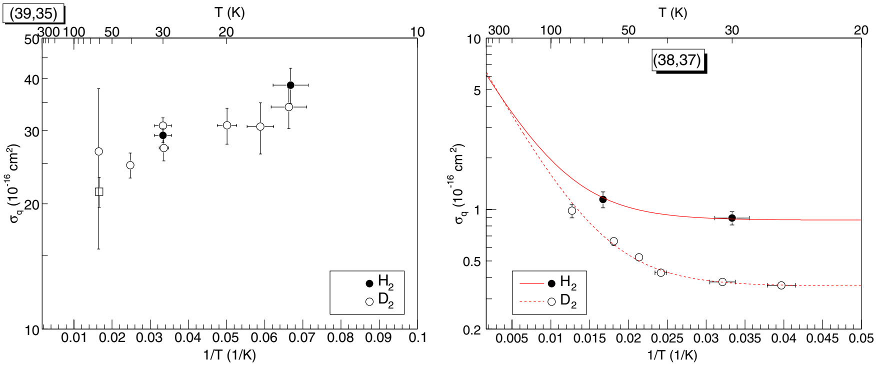

Figure 1: Left: Arrhenius plot of the newly and previously measured quenching cross sections of the state $(39, 35)$. Right: for comparison, previously measured data for the state $(38, 37)$. From [10].

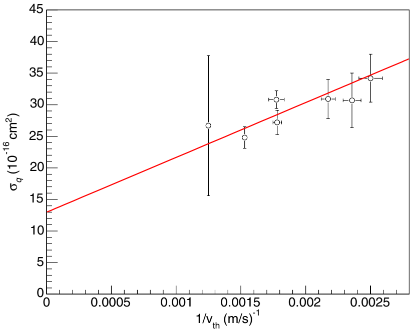

Figure 2: Quenching cross section σ_q of the state $(39, 35)$ with D_2 as a function of the inverse collisional velocity $1/v_{\rm th}$.

line; the correlation factor of the points is 0.849. Such a dependence of a cross section on the inverse velocity is consistent with the Wigner threshold law which states that in case of an exothermic reaction involving neutral particles near a threshold, the cross section is expected to follow an $1/v$ dependence in the low temperature limit [14]. The result of a fit of a straight line is also drawn in Fig. 2. We had no time to measure the quenching cross section above 60 K, therefore it is not known whether the cross section has a $1/v$ dependence at high temperatures as well, or on the contrary, it levels off around the geometric cross section $\sigma_{\rm geom} = 21 \times 10^{-16}$ cm^2.

Unfortunately, there are no theoretical calculations on the $\overline{\rm p}{\rm He}^+$–$H_2$ or $\overline{\rm p}{\rm He}^+$–$D_2$ system which would investigate the above-mentioned 'capture' mechanism and therefore it is not known whether it significantly increases the quenching cross section and if it does then whether it follows a $1/v$ dependence. There are, however, calculations on similar systems. One calculation on the H + H_2 and similar reactions found that the rate constants $K \approx \sigma v$ of the D + H_2 $\rightarrow$ DH + H and the D + DH $\rightarrow$ D_2 + H exothermic exchange reactions are independent of the temperature below ∼10 K [15], and another calculation on the relaxation of vibrationally excited H_2 molecules in collisions with ^{3}He and ^{4}He atoms found a $1/v$ dependence of the cross section of this process below ∼30 K [16].

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