FORMATION OF PROTONIUM IN COLLISIONS OF ANTIPROTONS WITH HYDROGEN

S. Yu. Ovchinnikov and J. H. Macek

Oak Ridge National Laboratory, Post Office Box 2008, Oak Ridge, TN 37831
Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996–1501

When antiprotons are trapped they undergo atomic reactions with background gases which remove them from the trap. They may capture into bound states with subsequent annihilation by nuclear interactions. An understanding of these processes requires reliable cross sections for low-energy collisions of antiprotons with atoms.

We have used the advanced adiabatic theory to compute protonium formation and ionization for low energy impact of antiprotons on atomic hydrogen. The advanced adiabatic method derives from an exact Sturmian representation, given by Ovchinnikov and Macek[1], of the full wave function for three particles interacting via electrostatic interactions. For that reason it must include all reaction channels, including protonium channels even though no protonium wave functions are included in the basis set. Even in the one-Sturmian approximation, which is crucial to the advanced adiabatic theory, all physical channels are included.

The conventional adiabatic electron energies for an electron in the field of $p + \overline{p}$ in the separated atom limit are the Stark energy levels of the H-atom in the field of the antiproton. At some finite distance, called the Fermi-Teller radius $R_{\rm FT} = 0.693...$, the electron just becomes unbound in the finite dipole field of the $p, \overline{p}$ system. At the united atom limit, where the antiproton coincides with the proton, the electron nuclei potentials cancel and the electron is completely free. The ground state potential curves $\varepsilon(R)$ therefore move into the continuum with decreasing internuclear separation and the bound states become quasi-stationary states. An approximate expression for $\varepsilon(R)$ for R less than $R_{\rm FT}$ is

$$\begin{aligned} \varepsilon_{n_1 n_2 m}(R) &= \tfrac{4}{R^2}\left(\lambda_0(R) - \tfrac{7}{2}\right) \\ &- i\tfrac{4}{R^2}(2n_1 + m + 1)\sqrt{8\lambda_0(R) - \tfrac{49}{4}} \end{aligned}$$

with

$$\lambda_0(R) = \left(n_2 + m + \frac{1}{2}\right)^2 - \frac{1}{2}\left(\frac{R}{n_2 + m + \frac{1}{2}}\right)^2 ,$$

where $n_1 n_2 m$ are the parabolic quantum numbers of a hydrogen in a constant electric field.

The advanced adiabatic theory of employs the quantity $R(\varepsilon)$ inverse to $\varepsilon(R)$. This quantity is the solution of the equation $\varepsilon(R) = \varepsilon$. The advanced adiabatic theory should be more reliable at the lower energies where the relative velocities of the heavy particles become much smaller than the electron velocities. In the region below the ionizaion threshold at 27.21 eV ionization occurs only by protronium formation. This allows a simple way to compute protonium formation in the advanced adiabatic theory, namely, we compute ionization without reference to the quantization of the protonium energies and then identify the cross section with protonium formation. This is convenient for computations of total protonium formation cross sections, but by using the $\frac{dE}{dn}$ energy interval weighting, n-distributions can also we obtained.

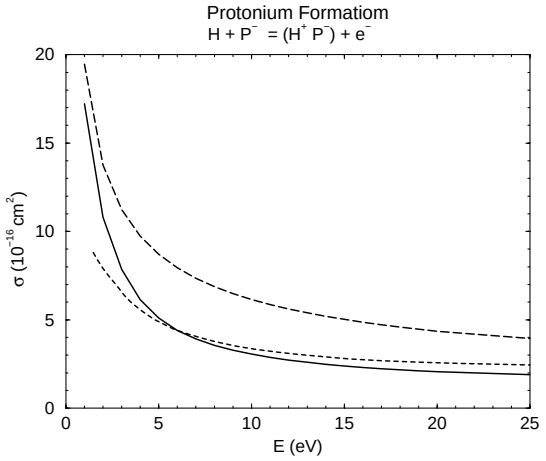

Figure 1: Cross sections for protonium formation. Short dash curve-CTMC from Schultz *et al*[2], long dash curve-upper limit orbiting cross section, solid curve-advanced adiabatic.

Figure 1 shows our protonium formation cross in the region below the ionization threshold at 27.21 eV. Also shown is the "upper limit" orbiting cross section $\sigma_p = \pi\sqrt{2\alpha_p/E}$. The orbiting effect is expected to become important as $E \to 0$. This trend is apparent in the advanced adiabatic calculations, but not in the CTMC results.

Acknowledgments

Supported by the Chemical Science, Geosciences and Biosciences Division, Office of Basic Energy Science, Office of Science, U.S. Department of Energy under Grant No. DE-FG02-02ER15283

References

1. S.Yu. Ovchinnikov and J.H. Macek, Phys. Rev. Lett. **80**, 2298 (1998).

2. D.R. Schultz *et al.*, Phys. Rev. Lett. **76**, 2882 (1996).