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Anti-Alpha Particle Impact Ionization of H and He

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ABSTRACT: The time-dependent Schrodinger equation is solved for the anti-alpha particle impact ionization of the H and He atoms. We report the cross section as a function of collision energy. Since neither theoretical calculations nor experimental measurements are available for such collision systems, we therefore compare our theoretical results with previous theoretical results and experimental measurements for antiproton impact ionization of the H and He atoms.

1. INTRODUCTION

Matter-antimatter interaction is fascinating and of fundamental interest. In 2011, the first conjugate of the helium nucleus or anti-alpha $(\bar{\alpha})$ candidates, the heaviest anti-nucleus observed so far, were observed by the STAR collaboration at the Relativistic Heavy-Ion Collider at the Bookhaven National Laboratory [1]. In 2018, the ALICE collaboration reported the measurement of the integrated production yield of the $\bar{\alpha}$ particle in their heavy-ion collisions experiment. The new analysis of the $\bar{\alpha}$ particle is based on data which was obtained during the run 1 of the Large Hadron Collider[2]. Subsequent new runs of the Large Hadron Collider and analyses are in the horizon and expected to produce an even higher statistical yield of the $\bar{\alpha}$ particles.

In contrast, the antiproton $(\bar{p})$ was first discovered in 1955. However, the first successfully experiment bearing on $\bar{p}$ in collisions with atoms (at CERN) did not come until 1986. Since then there has been many theoretical works dedicated to understanding the interactions between antiproton and atoms and molecules. In particular, the ionization of the first two elements in the periodic table, namely, H atoms and He atoms. A sample of theoretical results and discussions of the ionization cross sections for the two simplest atoms can be found in Ref.[3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. For more experimental and theoretical results and review on antiproton impact ionization of atoms and molecules, we refer the readers to Ref.[28]. Unlike proton-impact, the absence of the electron-transfer channel for antiproton-impact simplifies the theoretical calculations because one needs not follow the bound states of the moving projectile. The understanding of the atomic and molecular ionization processes by antiprotons is important for a reason that it has application in advance radiotherapy for cancer treatment [29, 30]. Having said that, perhaps, the discovery of anti-alpha particle maybe a great addition to anti-matter radiotherapy.

Anticipating that intense, well collimated, monoenergetic beams of low energy $\bar{\alpha}$ projectiles will be available in the future, like in the case of the antiproton in the FLAIR facility, in this paper the non-perturbative time-dependent close-coupling (TDCC) method[31] is employed to predict the single ionization cross section for the H and He atoms by $\bar{\alpha}$ particles. We compare the present theoretical results with TDCC theoretical cross sections[32] for the antiproton ionization of the H and He atoms and with experimental measurements[33] for the antiproton ionization of the H atom and experimental measurements[34, 35] for the antiproton ionization of the He atom.

2. THEORY

For anti-alpha particle collisions with the the H and He atoms:

$$H(\vec{r}, \vec{R(t)}) = -\frac{1}{2}\nabla^2 - \frac{Z_t}{r} + V_{HX}(r) + \frac{Z_p}{|\vec{r} - \vec{R(t)}|} \ . \tag{1}$$

The magnitude of the time-dependent position of the anti-alpha particle of nuclear charge $Z_p = 2$ moving in a straight line trajectory is given by:

$$R(t) = \sqrt{b^2 + (d_0 + vt)^2} \ , \tag{2}$$

where b is the impact parameter, d_0 is the starting distance, and v is the anti-alpha particle speed.

Expanding the total electronic wavefunction in spherical harmonics:

$$\Psi(\vec{r}, t) = \sum_{lm} \frac{P_{lm}(r,t)}{t} Y_{lm}(\theta, \phi) \tag{3}$$

yields the time-dependent close-coupled (TDCC) equations:

$$\begin{aligned} i\frac{\partial P_{lm}(r,t)}{\partial t} &= T_l(r) P_{lm}(r,t) \\ &+ \sum_{l'm'} W_{lm,l'm'}(r, R(t)) P_{l'm'}(r,t) \ . \end{aligned} \tag{4}$$

The one-body operator is given by:

$$T_l(r) = -\frac{1}{2}\frac{\partial^2}{\partial r^2} + \frac{l(l+1)}{2r^2} - \frac{Z_t}{r} + V_{HX}(r) \ . \tag{5}$$

The two-body operator is given by:

$$\begin{aligned} W_{lm,l'm'}(r, R(t)) = & \sum_{\lambda} \frac{(r, R(t))_<^{\lambda}}{(r, R(t))_>^{\lambda+1}} \sum_q C_q^{\lambda *}(\theta_p, \phi_p) \\ & \times (-1)^m \sqrt{(2l+1)(2l'+1)} \\ & \begin{pmatrix} l & \lambda & l' \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l & \lambda & l' \\ -m & q & m' \end{pmatrix} \ , \end{aligned} \tag{6}$$

where λ and q are multipole expansion coefficients and $C_q^{\lambda}(\theta, \phi)$ is a spherical tensor.

The initial condition for the solution of the time-dependent close-coupling equations is given by:

$$P_{lm}(r,t) = P_{1s}(r)\delta_{m,0} \ . \tag{7}$$

A 768-point radial mesh with a mesh spacing $\Delta r = 0.10$ is used for solving the the time-dependent close-coupling equations. We considered the projectile travels rectilinearly from -50 a.u. to +50.0 a.u. Anti-alpha particle probabilities are obtained at asymptotic time by projecting the time-propagated $P_{lm}(r, t)$ radial wavefunctions onto bound orbitals and subtracting from 1 for each of 70 impact parameters ranging from $b = 0.1$ to $b = 18.0$. The probabilities are then used to obtain total cross sections at a given incident energy.

3. RESULTS

We carried out the TDCC calculations for the $\bar{\alpha}$-impact single ionization of the 1s subshell of the H atom at 15 different incident energies. The ionization cross sections are given in Table 1. The TDCC theoretical calculations for the $\bar{\alpha}$-impact ionization of the Hydrogen atom are compared with TDCC theoretical calculations[32] and experimental measurements[33] for the $\bar{p}$-impact ionization of the H atom in Figure 1. It is shown that the ionization due to $\bar{\alpha}$ particle impact are much larger than those of $\bar{p}$. Qualitatively, this is expected because the nuclear charge of $\bar{\alpha}$ particle is twice of $\bar{p}$. Quantitatively, the theoretical $\bar{\alpha}$-impact ionization cross section is about an order of magnitude larger than those of $\bar{p}$ across the energy in question.

For a fast and bare projectile ion with positive charge Z_p traveling with incident velocity v relative to a hydrogen atom target, a scaling law for predict ionization cross sections σ_{ion} due to projectile ion of arbitrary charge and incident velocity [36, 37, 38, 39, 40] is given by

$$\sigma_{ion}(Z_p, v) = Z_p^a \sigma_{ion}(1, v), \tag{8}$$

where a is velocity dependent and tends to the value two at asymptotically high energies. It has been shown that for projectile with charge states of Z_p = +1 to +4, beyond incident energy of 100 keV/amu, the value of a is determined to be $\sim$1.8 [36], demonstrating its tendency towards Z_p^2 scaling law. On the other hand, in our case the projectile charge state increases from Z_p = -1 to -2, at 100 keV/amu we found that the theoretical ratio: $\sigma_{ion}^{\bar{\alpha}}/\sigma_{ion}^{\bar{p}} \sim 10$. This is unexpected as it deviates from the Z_p^2 scaling law. And unlike the ionization trend seen by $\bar{p}$ projectile, the $\bar{\alpha}$-impact ionization cross sections appear to oscillate weakly as the energy decreases below 30 keV.

Next, we examine the $\bar{\alpha}$-impact single ionization of the $1s^2$ subshell of the He atom at 15 different incident energies. To model the one-electron He atom, we used the Hartree with local exchange potential $V_{HX}(r)$ in Eq.(1) from our previous work [4]. The TDCC calculations were carried out at 15 different incident energies and the ionization cross sections are also tabulated in Table 1. In Figure 2, we compare the $\bar{\alpha}$-impact ionization of the He atom with TDCC theoretical calculations [32] and experimental measurements[34, 35] for the $\bar{p}$-impact ionization of the He atom. Using the scaling law to estimate, for the He target, as the projectile charge state increases from Z_p = -1 to -2, at 100 keV/amu we found that the theoretical ratio: $\sigma_{ion}^{\bar{\alpha}}/\sigma_{ion}^{\bar{p}} \sim 5$. This seems to align with our familiar Z_p^2 scaling law. However, again, unlike the ionization trend seen by $\bar{p}$ projectile, as the energy decreases, the $\bar{\alpha}$-impact ionization cross sections appear to decrease to a minimum at around 15 keV and increase again after that energy. Notice that the theoretical $\bar{p}$-impact ionization cross sections have similar energy dependence despite the targets (i.e., H and He) are different.

The substantial difference in the magnitude between the $\bar{\alpha}$-impact cross sections and the $\bar{p}$-impact cross sections are mainly due to two factors. The first factor is the increase in the projectile charge from Z_p = -1 for the antiproton to Z_p = -2 for the anti-alpha particle. Thus the interaction term in Eq.(1) becomes larger. The second factor is the increase in the projectile mass from m_p = 1 for the antiproton to m_p = 4 for the anti-alpha particle. Thus the scattering angle[31] is reduced allowing the projectile and target to interact more strongly as the projectile passes the target.

4. SUMMARY

In summary we solved the time-dependent Schrodinger equation for the anti-alpha particle ionization of the H and He atoms in the collision energy range between 1.0 keV and 100.0 keV. Since there is neither theoretical calculations or experimental data for such a collision system, we therefore compare the theoretical results with previous theoretical calculations[32] for the antiproton ionization of the H and He atoms and with experimental measurements[33] for the antiproton ionization of the H atom and experimental measurements [34, 35] for the antiproton ionization of the He atom. For future work, we may investigate the energy and angular dependent differential cross sections for the $\bar{\alpha}$-impact ionization of the H and He atoms.

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Table 1. Single ionization cross sections [Mb] for H and He atoms.

Energy [keV]	H atom	He atom
1.0	1030	353
2.0	1070	340
3.0	1010	320
4.0	1110	329
5.0	1060	325
10.0	990	315
15.0	940	308
20.0	980	324
25.0	950	322
30.0	970	330
40.0	970	342
50.0	960	354
60.0	940	364
75.0	910	364
100.0	850	371

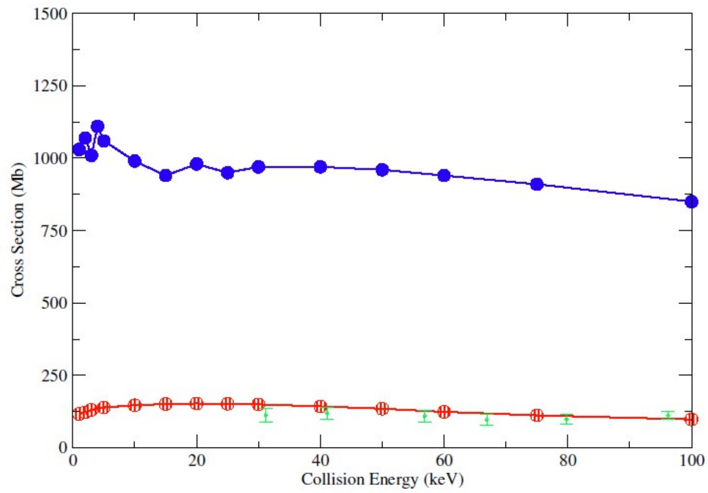

Figure 1. Single Ionization of H. Solid blue circles: TDCC for anti-alpha particle, striped red circles: TDCC for antiproton particle, error bar circles: Experiment for antiproton particle (1.0 Mb = 1.0 X 10 $^{-18}$ cm^2).

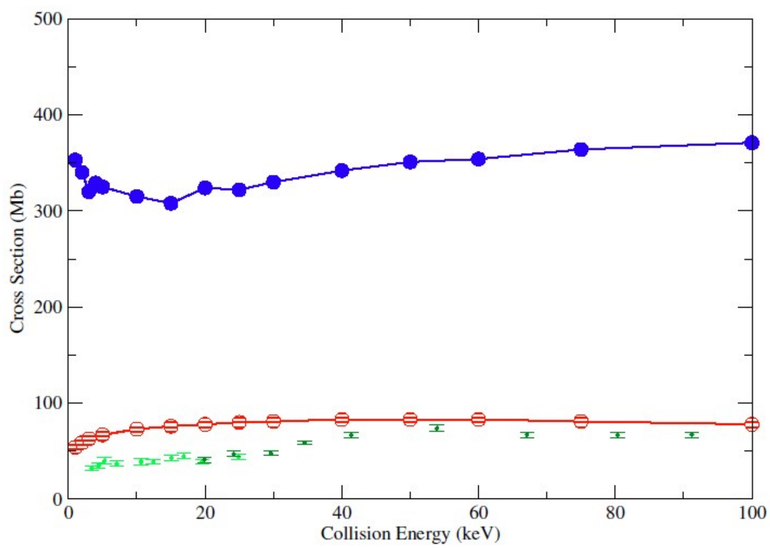

Figure 2. Single Ionization of He. Solid blue circles: TDCC for anti-alpha particle, striped red circles: TDCC for antiproton particle, error bar circles: Experiment for antiproton particle (1.0 Mb = 1.0 X 10 $^{-18}$ cm^2).