# Scattering correlation in double ionization of helium by fast antiprotons and protons

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The difference between the double-ionization cross sections of antiprotons and protons colliding with helium may be explained by the distortion of the two-electron wave function during the collision. The distortion is related to the presence of electron-electron correlations and depends on the sign of the projectile charge. The proposed correlation effect requires an at-least-partly-adiabatic behavior for target electrons. The existence of adiabaticity in high-energy large-impact-parameter collisions is discussed. By building in the effect of distortion into the center-of-charge interaction formulation of the independent-particle model, the calculated cross sections are in agreement with the experimental values.

## I. INTRODUCTION

In the experiment of Andersen *et al.*[1] a marked difference between the double-ionization cross sections for 0.5–5-MeV antiprotons and protons colliding with helium has been found. The cross-section values for antiprotons are approximately a factor of 2 larger than those for protons. This result indicates the shortcoming of the independent-particle model (IPM) (Ref. 2) which has served until now[3] as a reliable tool for the study of collisions between charged particles and many-electron atoms. In the IPM the atom is treated as a collection of electrons which independently interact with the projectile. The interpretation of data[1] calls for the refinement of the IPM by including terms related to the electron-electron correlations. Corrections to the IPM due to the effect of electron correlation have been described by Ford and Reading[4] and McGuire.[5]

In the recent model of Reading and Ford[6] based on the coupled-channel method, the collision time is divided into segmented pieces short enough that the electron-electron interaction can be neglected during the time evolution within each time segment. At the end of each segment the electron-electron interaction is switched on allowing the system to collapse back into a correlated eigenstate. The sophisticated calculations have reproduced a part of the observed effect and predicted its disappearance at projectile energies of a few tens of MeV/amu.

In this paper we describe a simple mechanism to explain why the antiproton-helium double-ionization cross section is larger than that for proton. In the proposed scheme the projectile interacts with each of the two electrons and the electron-electron correlation affects the process of the projectile-remote-electron collisions.

## II. THE MODEL

Before discussing the correlation effect we investigate the concept of collision time in high-energy ion-atom collisions. Generally the collision time $T_{\rm coll}$ is taken as $T_{\rm coll}=2R/v$, where $R$ is the radius of the atomic orbit and $v$ is the velocity of the projectile. This definition of $T_{\rm coll}$ is suitable for low-energy collisions which are close collisions with impact parameters $B<R$. The definition of $T_{\rm coll}$ for high-energy collisions, where the region $B>R$ gives important contributions (see, for example, the table of Hansteen *et al.*[7]), needs more care. To estimate $T_{\rm coll}$ for impact parameters $B>R$, we calculate the time development of the momentum-transfer process via Coulomb interaction between an electron and a proton moving swiftly by. We assume that the electron has not considerably changed its position before the proton passed by. For a projectile having a straight-line orbit along the $z$ axis (see Fig. 1), the transversal component $q_\perp$ of the momentum transfer can be calculated as

$$q_\perp=e^2\int_{-\infty}^{\infty}\frac{1}{b^2+z^2}\sin\theta\,dt=\frac{2e^2b}{v}\int_0^{\infty}\frac{dz}{(b^2+z^2)^{3/2}}=\frac{2e^2}{bv}\ . \tag{1}$$

The momentum transfer $q_\perp(z_0)$ imparted to the electron in the $[-z_0,z_0]$ interval is given as

$$q_\perp(z_0)=\frac{2e^2b}{v}\int_0^{z_0}\frac{dz}{(b^2+z^2)^{3/2}}=\frac{2e^2}{bv}\frac{z_0}{(z_0^2+b^2)^{1/2}}\ . \tag{2}$$

For example, the electron gets 90% of $q_\perp$ at the limit $z_0\simeq 2b$. We estimate $T_{\rm coll}$ as the time needed to cover the $4b$ distance

$$T_{\rm coll}\equiv\frac{4b}{v}\ . \tag{3}$$

This estimate of $T_{\rm coll}$ is suitable for a large-impact-parameter collision where $R$ is small enough compared to $B$. In this case the parameter $b$ could be identified with the impact-parameter $B$, since here the amplitude of the electron motion inside the atom does not appreciably change the projectile-electron distance along the projectile path.

According to the table in Ref. 7 for an He atom ionized by 0.5–5-MeV energy protons, more than 80% of the contributions to the cross section comes from the

 

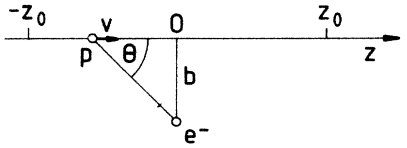


FIG. 1. Diagram used to calculate the momentum transferred to an electron via the Coulomb interaction with a fast projectile. If $z_0=2b$, covering the $[-z_0,z_0]$ interval the electron gets 90% of the whole imparted momentum.

impact-parameter region $B>R_0$ with $R_0=a_0/Z_{\text{eff}}$, where $a_0$ is the Bohr radius and $Z_{\text{eff}}=1.7$ is the screened atomic number of the helium atom. The maximum contribution comes from the impact parameter $B\approx 2R_0$. Regarding the estimate (3), $T_{\text{coll}}$ can be written as

$$T_{\text{coll}}\approx 8\frac{R_0}{v} . \tag{4}$$

The relation of $T_{\text{coll}}$ to the time $\tau$ needed for the orbital electron to cover a distance as large as the atomic radius is

$$T_{\text{coll}}\approx 8\frac{R_0}{v_0}\frac{v_0}{v}=8\frac{v_0}{v}\tau , \tag{5}$$

where $v_0$ is the orbital velocity of the electron. This equation suggests that for projectile velocities $v\lesssim 10v_0$, the orbital electron can respond to the motion of the projectile. We can say that at large impact parameters the high-energy ion-atom collisions have some adiabatic properties.

Now we discuss an effect of the electron-electron interaction which may explain the enhanced double ionization of helium by antiprotons. Since the 0.5–5-MeV projectile energy region the relation $v\lesssim 10v_0$ fulfills, we can assume the existence of the response motion of the atomic electrons. Due to their mutual repulsion the two electrons of the helium atom favor positions on opposite sides of the nucleus. Considering the polarization of the initial two-electron wave function of helium, the two projectile-electron interactions cannot be treated independently. The proton attracts the near-side electron stronger than the far-side one, which, due to the electron-electron interaction, moves away from the projectile [see Fig. 2(a)]. For antiprotons, due to the repulsive interaction, the near-side electron moves away and the far-side electron comes nearer to the projectile [see Fig. 2(b)]. We can say that the initial state and, therefore, the ejection probability of the far-side electron depends on the sign of the projectile charge.

Our aim is to build the proposed correlation effect into the framework of the IPM. Regarding the high incident energies, we can choose the center-of-charge interaction formulation[8] of the IPM. In this model, which offers a good approximation for the description of distant collisions, the scattering amplitude of the multielectron transitions is calculated as the first Born matrix element of the Coulomb interaction acting between the projectile and the center of charge of the target electrons. In the center-of-charge interaction approximation (CCIA) the momentum-transfer $q$ imparted to the atomic electrons is shared in equal amounts among them. For the helium target the scattering amplitude is written as

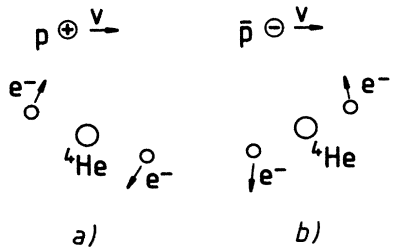


FIG. 2. Owing to the electron-electron correlations, the far-side electron moves away from the proton (a) and comes nearer to the antiproton (b) projectile.

$$T_{fi}=\frac{-Ze^2\hbar^2}{\pi^2 q^2}\left\langle \phi_f(\mathbf{r}_1,\mathbf{r}_2)\left|\exp\left[-i\frac{\mathbf{q}}{2}(\mathbf{r}_1+\mathbf{r}_2)\right]\right|\phi_i(\mathbf{r}_1,\mathbf{r}_2)\right\rangle , \tag{6}$$

where $Z$ is the projectile charge and $\mathbf{r}_1,\mathbf{r}_2$ are the coordinates of the target electrons measured from the target nucleus. $\phi_i$ and $\phi_f$ denote the ground and final states of the helium atom, respectively. The total cross section of the double-ionization process for helium atom has the form

$$\sigma_2=8\pi\left[\frac{Ze^2}{v}\right]^2\int_{q_{\min}/2}^{q_{\max}/2}\frac{dq}{q^3}f(q)^2 , \tag{7}$$

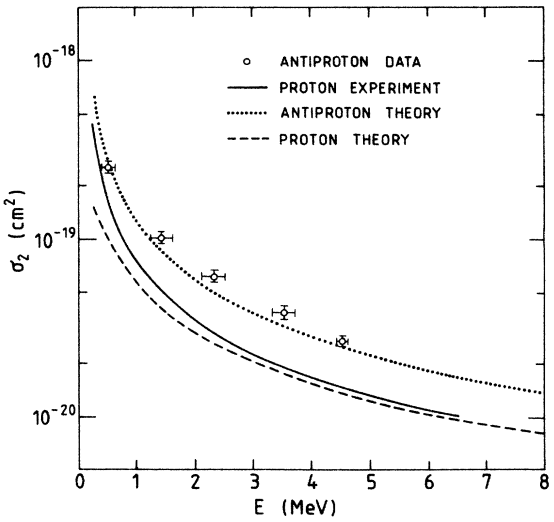


FIG. 3. The measured and calculated double-ionization cross sections for the helium target. The experimental curve and data points are taken from Andersen *et al.* (Ref. 1).

where $f(q)$ is given by the elastic form factor of the $1s$ single-electron state

$$f(q)=1-\left|\left\langle\varphi_{1s}(\mathbf{r})\left|\exp\left[-i\frac{\mathbf{qr}}{\hbar}\right]\right|\varphi_{1s}(\mathbf{r})\right\rangle\right|^2 . \quad (8)$$

We choose the limit of integration as

$$q_{\min}=\Delta E/2v, \quad q_{\max}=\left[q_{\min}^2+\left[\frac{\hbar}{2\langle r\rangle}\right]^2\right]^{1/2}, \quad (9)$$

where $\Delta E$ is the sum of the total binding energy of the helium atom and the average kinetic energies of the two ionized electrons. The latter term is taken as if the electrons were ejected at velocities half of the orbit velocity.[9] $\langle r\rangle$ is the radial expectation value of the helium atom. The choice of $q_{\max}$ is suggested by the uncertainty principle.[10] For values $q>q_{\max}$ the collision cannot be treated as a distant one and the CCIA becomes invalid.

The proposed correlation effect may be simulated by a shift in the impact parameter of the projectile-far-side-electron collision. To take into account this effect, in the integral in Eq. (7) we make the following modification:

$$f^2(q)\rightarrow f(q)f(q') , \quad (10)$$

where $q'$ is chosen as follows. The characteristic impact parameter for the momentum transfer $q$ is $B=\hbar/q$. For incident protons the effective increase of the impact parameter by $\Delta B$ results in the value of $q'$ as

$$q_p'=\hbar/(B+\Delta B)=q\Big/\left[1+\frac{q\Delta B}{\hbar}\right] \quad (11)$$

and for antiprotons due to the effective decrease of $b$ we obtain

$$q_{\bar{p}}'=\hbar/(B-\Delta B)=q\Big/\left[1-\frac{q\Delta B}{\hbar}\right] . \quad (12)$$

For the helium atom the value of the $\Delta B$ shift may have the order of the atomic radius. For the calculations we have used, screened hydrogenic wave functions[11] and the results with the optimum value $\Delta B=0.8\langle r\rangle$ are presented in Fig. 3. The satisfactory agreement between the experimental and theoretical values suggests that the proposed correlation effect could describe the difference between the antiproton and proton cross sections. Since the discussed correlation effect is less expressed for atoms containing more electrons, our model predicts that the difference between the antiprotonic and protonic multi-ionization cross sections should decrease with the increase of the atomic number of the target.

The possibility of electron response motion decreases with increasing projectile energy, see Eq. (5); therefore, the model incorporates the decrease of the effect with increasing projectile energy in accordance with the prediction.[6]

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[10]$q_{\min}$ and $q_{\max}$ differ from the limits used in the original paper of the CCIA in Ref. 8. In Ref. 8 the kinetic energies for the lower limit and the choice of $q_{\max}$ were fixed by classical arguments based on the kinematics of the Rutherford scattering. The present choice given in Eq. (9) better suits the quantum-mechanical treatment.
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