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Single-electron capture in $p-\mathrm{He}^{+}$ collisions

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Introduction

Electron capture in collisions between fast ionic projectiles with atomic targets has been a subject of significant interest for decades. Cross sections for such processes play a crucial role in estimating the energy losses of ions during their passage through matter of varying kinds. Cross sections databases find useful applications in both pure physics areas, such as plasma physics, astrophysics and heavy ion transport physics, as well as interdisciplinary, such as fusion energy research and medical physics.

Theory

We consider single-electron capture into all final states Σ in collisions between fast protons p and helium ions He^{+} in the ground state:

$$p+\mathrm{He}^{+}(1\mathrm{s}) \to \mathrm{H}(\Sigma)+\mathrm{He}^{2+}. \quad (1)$$

We will calculate the state-summed total cross sections in the framework of the boundary-corrected first Born approximation (CB1-3B). This high energy theory is a fully quantum-mechanical approach, which strictly preserves the correct boundary conditions in both the entrance and exit collision channels [1, 2, 3]. The prior form of the transition amplitude for capture into an arbitrary nlm final state is:

$$T_{if}(\vec{\eta}) = Z_{\mathrm{P}} \int\int \mathrm{d}\vec{s}\mathrm{d}\vec{R}\varphi^{*}_{nlm}(\vec{s})\left(\frac{1}{R}-\frac{1}{s}\right) \times \varphi_i(\vec{x})\mathrm{e}^{i\vec{\beta}\cdot\vec{R}-i\vec{v}\cdot\vec{s}}(vR+\vec{v}\cdot\vec{R})^{i\xi}, \quad (2)$$

where $Z_P = 1$ is the projectile charge, $\vec{\beta} = -\vec{\eta}-\beta_z\hat{\vec{v}}$ the momentum transfer ($\beta_z = v/2+\Delta E/v$), $\Delta E = E_i - E_f$ the difference between the initial and final bound-state energies, $\vec{v}$ the projectile velocity, $\vec{\eta} = (\eta\cos\phi_\eta, \eta\sin\phi_\eta, 0)$ the transverse momentum transfer vector ($\vec{\eta}\cdot\vec{v} = 0$), and $\xi = (Z_P - Z_T)/v$. The position vector of the electron relative to the projectile (target) is $\vec{s}$ ($\vec{x}$), and $\vec{R}$ is the relative position vector of the projectile to the target. Finally, $\varphi_i(\vec{x})$ and $\varphi_{nlm}(\vec{s})$ are the initial and final bound-state wave functions, respectively. The six-dimensional integral for the transition amplitude matrix elements T_{if} from Equation (2) can be reduced to a one-dimensional integral over a real variable in the interval $[0, 1]$. The state-resolved total cross sections become:

$$Q_{nml} \equiv Q_{if}(a_0^2) = \frac{1}{2\pi v^2}\int_0^{\infty} d\eta\eta|T_{if}(\vec{\eta})|^2. \quad (3)$$

Numerical integration of the two-dimensional integral in Equation (3) over the two real variables is performed using Gauss-Legendre quadrature. The state-summed total cross sections for capture into all final states are obtained by applying the Oppenheimer n^{-3} scaling law [4]:

$$Q \equiv Q_{\Sigma} = Q_1 + Q_2 + Q_3 + 2.561Q_4, \quad (4)$$

with the state-resolved cross sections Q_n and Q_{nl} being:

$$Q_n = \sum_{l=0}^{n-1} Q_{nl}, \quad Q_{nl} = \sum_{m=-l}^{+l} Q_{nlm}. \quad (5)$$

Results

The present CB1-3B results exhibit a very good agreement with all the available measurements [5, 6, 7], as seen in Figure 1. The discrepancies are very slight, and for the highest energy data point the theory approaches the experimental cross section value within the measurement error. Since CB1-3B is a high energy theory, and the available measurements are all in the intermediate energy range, some discrepancy is indeed natural. The agreement is nevertheless satisfactory, and is expected to improve even further for higher energy values.

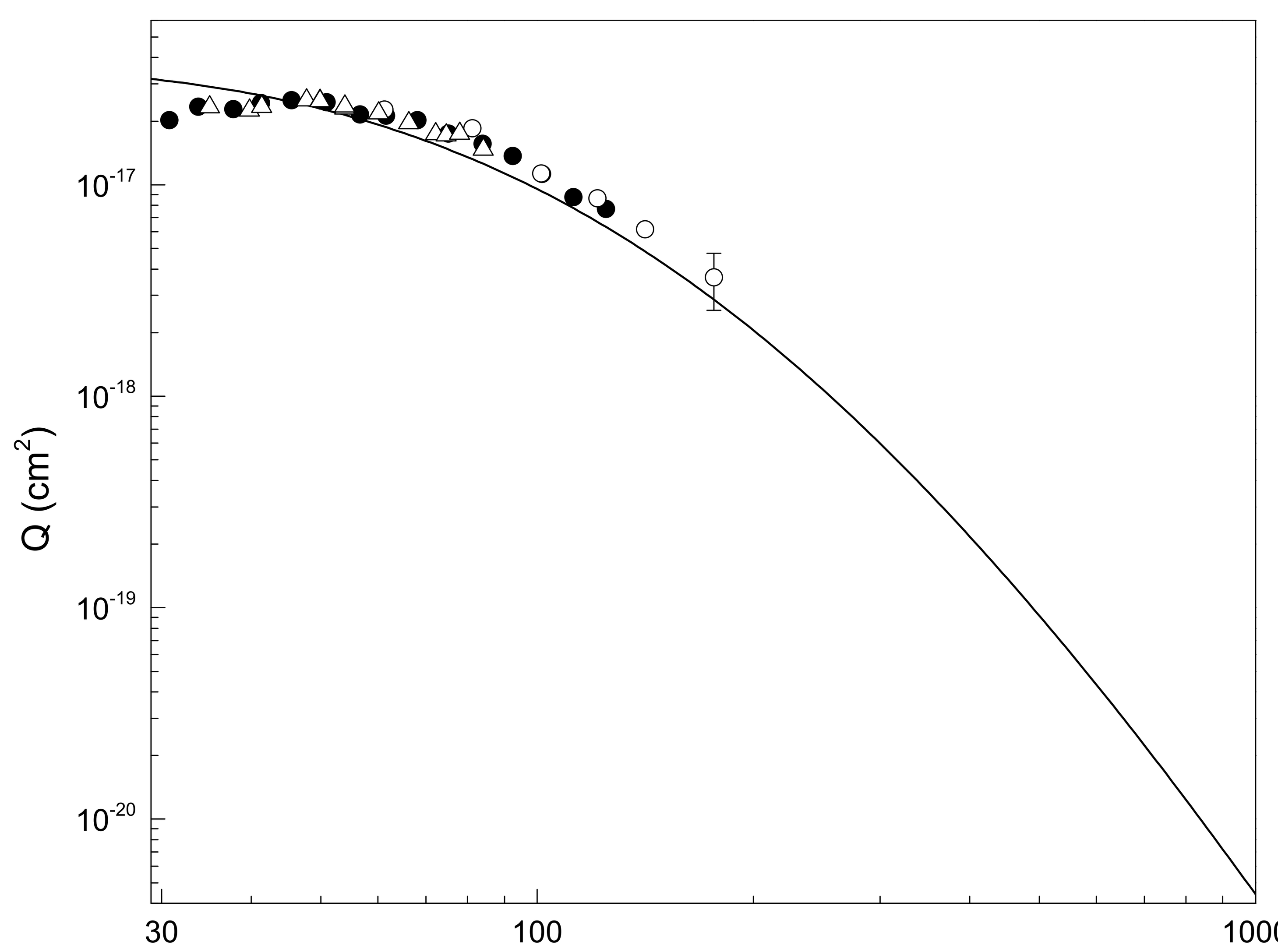

Figure 1: State-summed total cross sections as a function of impact energy E (keV) in the laboratory frame of reference for single-electron capture into all final bound states $\mathrm{H}(\Sigma)$ from the ground state of the helium ion $\mathrm{He}^{+}(1\mathrm{s})$ by protons. The full curve is the present result in the CB1-3B method. Experimental data: △ Peart et al. 1983, • Rinn et al. 1985, ○ Watts et al. 1986.

Conclusion

This work provides us with useful total cross section values for the process of single-electron capture in collisions between protons p and helium ions He^{+}, as well as representing a critical test of the validity of the CB1-3B approximation. After contrasting it with the experimental data for this genuinely three-body single-electron capture process, we conclude that the agreement is very satisfactory, and therefore the validity of the CB1-3B method is strongly confirmed.

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References

[1] Belkić Dž., Gayet R. and Salin A., *Phys. Rep.* 56, 279 (1979)
[2] Belkić Dž., *Principles of Quantum Scattering Theory*, Institute of Physics, Bristol (2004)
[3] Belkić Dž., *Quantum Theory of High-Energy Ion-Atom Collisions*, Taylor & Francis, London (2008)
[4] Oppenheimer J. R., *Phys. Rev.* 31, 349 (1928)
[5] Peart B., Rinn K. and Dolder K., *J. Phys. B: At. Mol. Opt. Phys.* 16, 1461 (1983)
[6] Rinn K., Melchert F. and Salzborn E., *J. Phys. B: At. Mol. Opt. Phys.* 18, 3783 (1985)
[7] Watts M. F., Dunn K. F. and Gilbody H. B., *J. Phys. B: At. Mol. Opt. Phys.* 19, L355 (1986)