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Total ionization cross sections in particle and antiparticle collisions with rare gases

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Abstract

In this contribution we analyze the total ionization cross sections by impact of electrons, positrons, protons and antiprotons in Ne, Ar, Kr and Xe. We compare theoretical results using the continuum distorted wave eikonal initial state approximation with a detailed compilation of the available experimental data for the four projectiles in each target. The charge and mass effects, and the convergence at intermediate energies are discussed, which are important issues for antiparticle normalization. We remark the influence of the post-collisional Auger-like electron emission, which is decisive to describe the total ionization of Kr and Xe at impact velocities above 9 a.u.

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1. Introduction

Total ionization cross sections have been experimentally and theoretically studied for years. Reviews and compilations of data are available in the literature. For example, the electron impact compilations by Tawara and Kato (1987) [1] and by de Heer *et al* (1979) [2], and the review and suggested values for proton impact by Rudd *et al* (1985) [3]. The research on antiparticle impact processes has became a very active field in the last three decades. A recent *state of art* of antiproton impact ionization can be found in [4], and for developments and applications of the physics of positron impact in [5]. Well-known reviews on particle and antiparticle collisions are those by Schultz *et al* (1991) [6] and by Knudsen and Reading (1992) [7].

In this contribution we focused on the total ionization cross sections by $|Z| = 1$ projectiles, i.e. protons, antiprotons, electrons, and positrons, with a double purpose:

- to analyze the charge and mass effects, and convergence at high energies, important for antiparticle normalization,

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- to show the influence of post-collisional ionization in the total ionization at high impact energies.

The differences in the ionization cross sections by light (electrons and positrons) and heavy (protons and antiprotons) projectiles in the intermediate to low energy region is experimentally clear. The theoretical description of these collisions involves considering the projectile trajectories, finite momentum transferred and the energy thresholds. In the high energy region all these cross sections are expected to converge. However, this convergence and the minimum impact velocity for these cross sections to be equal is different for antiprotons, positrons or electrons. Usually the antiproton and positron data are normalized to electron data at high energies rather than to proton impact values. One of the objectives of this work is to present a broad view of the convergence of the different $|Z| = 1$ projectiles and possible alternatives for the antiparticle normalization, even at lower energies than 1 keV employed up to now [8, 9].

In the high energy region the post-collisional ionization is also important, which affects also the total ionization cross sections [10]. The post-collisional electron emission is a consequence of the ionization of the inner-shells that ends in multiple ionization due to rearrangement of the excited target (Auger-type processes). The manner of including the post collisional ionization within the total cross sections is by calculating the multiple ionization, both in direct collisions and in post collisional processes [11]. To analyze the particle-antiparticle behavior we consider the ionization of the heaviest rare gases (from Ne to Xe) by proton, antiproton, electron and positron impact. An extended compilation of the available data in comparison with the ab-initio CDW-EIS total cross sections [10, 11, 12, 13] is presented for the sixteen systems considered (four projectiles and four targets). The values studied here are pure ionization, not including charge transfer (for proton impact) or positronium formation.

In section 2 we summarize the theoretical calculations of total ionization cross sections from the multiple ionization values, and the inclusion of post collisional contributions. In section 3 we display and discuss the comparison of the total ionization values for the four projectiles. Finally some conclusions are presented in section 4

2. Theoretical considerations about the total ionization cross sections

The total ionization cross section, σ_{Total}, is calculated theoretically as

$$\sigma_{Total} = \sum_{nlm} \sigma_{nlm} \tag{1}$$

with σ_{nlm} being the contribution of the ionization of an electron initially in the nlm sub-shell. This value is also known as the inclusive single ionization cross section (ionization of at least one electron). Instead, the multiple ionization cross section $\sigma_{(q)}$ of exactly q electrons is known as exclusive cross section [14]. The gross cross and count cross sections are defined as different additions of the multiple ionization values as

$$\sigma_{gross} = \sum_{q} q\, \sigma_{(q)} \tag{2}$$

and

$$\sigma_{count} = \sum_{q} \sigma_{(q)}. \tag{3}$$

Physically, σ_{gross} is a measure of total electron production, while σ_{count} measures the production of positive ions. The *count/gross* difference is known and tabulated experimentally [2]. However, *total* ionization cross section has been used indistinctly for *gross* or *count* cross sections, producing misunderstandings. For example, in a recent review by Chiari *et al* (2014) [15] a discrepancy between the data by Marler *et al* (2005) [16] and by van Reeth *et al* (2002) [17] is mentioned, without noting that count cross sections were compared with gross cross sections. Similarly, the electron impact *count* cross sections by Sorokin *et al* (2000) [18] have been compared with the theoretical gross cross sections by Bartlett and Stelbovits (2002) [19], with the reasonable disagreement for Kr and Xe at high energies.

Sant'Anna *et al* (1998) [14] demonstrated that σ_{Total} given by Eq. (1) is exactly the same that σ_{gross} given by Eq. (2).

$$\sum_{nlm} \sigma_{nlm} = \sum_{q} q\, \sigma_{(q)}, \tag{4}$$