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Tandem-method for measurement of destruction cross-sections of neutral projectiles at intermediate and high velocities

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Abstract

We have recently presented destruction cross-section data for *negative ions* obtained with a technique that uses the gas stripper of a tandem accelerator as the collision target. In this work, we develop an extension of that technique to measure destruction cross-sections for *neutral projectiles*, important parameters to estimate neutral beam attenuation in Heavy Ion Fusion applications. Measurements for the $H + N_2$ collision system are used to exemplify and discuss the capabilities and limitations of the proposed experimental method.

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1. Introduction

The use of high-velocity neutral beams has been considered for Heavy Ion Fusion (HIF) possible scenarios (e.g. Refs. [1–6]). Neutralization at some stage after final focusing can, in principle, overcome problems due to the huge space charge of intense ion beams. Once neutralized, it is desirable that these high-velocity projectiles do not lose electrons. However, interaction of beam particles with the fusion-chamber environment can lead to beam ionization by several mechanisms [7]. Beam electron stripping in collisions with background gas is one of these mechanisms and destruction cross-sections, σ_0^d (also called stripping or total electron-loss cross-sections) are parameters needed to quantify the fraction of the initially neutral beam that can reach the fusion target [1,2].

There is a considerable amount of experimental data for these cross-sections at low projectile velocities, v, (compared to the Bohr velocity v_B, equivalent to $E = 25\,\text{keV/u}$). On the other hand, high-velocity data are very scarce in the literature (e.g. Refs. [8,9]). The reason for this asymmetry is basically the difficulty of preparing a good-quality neutral beam at high velocities that can be subsequently used as an incoming beam in a collision experiment. Producing neutral beams at $v < v_B$ is relatively simple, as positive projectiles present huge electron capture cross-sections at these velocities. Therefore, a neutral beam can be efficiently created through neutralization of positive ions going through a gaseous chamber. A rather distinct picture arises at intermediate and high velocities, since capture cross-sections decrease very sharply with projectile velocity. Thus, alternative strategies must be used to measure σ_0^d. In the traditional growth-rate method [8,10] (hereafter called traditional method), a negative-ion beam is prepared and crosses a gas target with controlled variable pressure. Final-charge-state fractions, F_j, are measured as a function of the gas-cell line density (the product of the gas density and effective length of the cell), x. Qualitatively, the idea is to prepare the neutral beam inside the collision target itself (through a first collision) and let it collide, at least once more, with other atoms in the gas cell. The difficulty here is that, for usual experimental setups, a high-velocity anion beam is more difficult to obtain than the corresponding equivelocity positive beam. Ranges of all the available data [8,11,12], to our knowledge, for the N_2 target and any neutral projectile are shown in Fig. 1. The highest-velocity available datum for multielectron projectiles is that for $1\,\text{MeV/u}$ $Li^{0+} + N_2$ [11,12].

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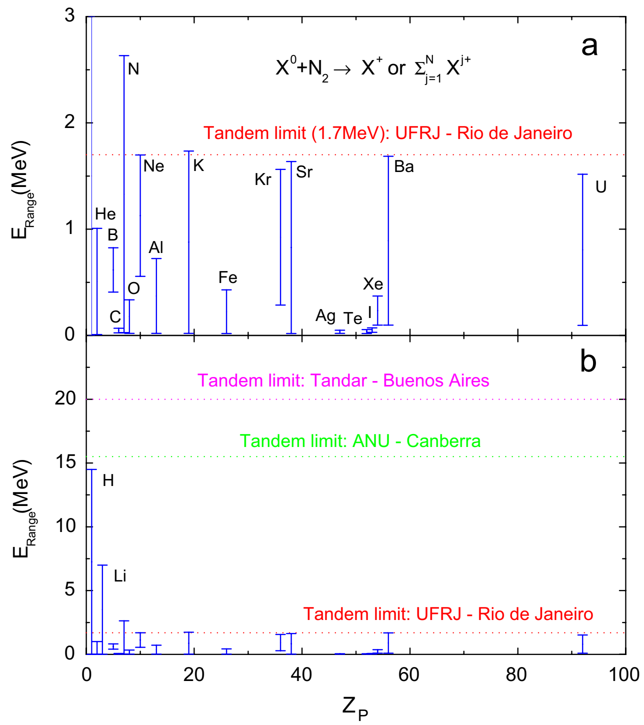

Fig. 1. Cross-section energy ranges for electron loss of neutral projectiles impinging on N_2, as a function of the atomic number of the projectile. Dotted lines represent examples of energy limits of accelerators: (a) the UFRJ Tandem limit is compared to ranges of available data; (b) highlights the lack of data at high velocities and show limits of other accelerators.

Our group at UFRJ has developed a variation of the growth-rate method that uses the gas stripper of a tandem accelerator as the collision target to determine the *anion* destruction cross-section, σ^d_{-1} [13]. The line density is calibrated against the pressure at the exit of the accelerator column. One high-velocity well-known σ^d_{-1} value is needed for normalization. If a H^{i+} beam is used for the calibration, compiled values for the six possible charge-exchange cross-sections σ_{ij} $(i,j=-1,0,1)$ [9] can be used (σ_{ij} is the charge-changing cross-section from i to j) and the measurement of $F_0(x)$ improves the calibration [13]. The inversion of this procedure, i.e., obtaining individual cross-sections from fitting parameters is not straightforward, particularly for many electron projectiles, and is discussed in the next section.

We have studied several anionic-projectile collision systems (e.g. Ref. [14]) including halogen anions incident on N_2 [15], motivated in the latter case by a proposal to produce neutral beams for HIF from the photoionization of halogen anions [1]. In this paper, we present and discuss an extension of that method (hereafter called Tandem method) to measure destruction cross-sections σ^d_0 for any *neutral* atomic projectile, provided that it has a stable anion.

2. Tandem method versus traditional method

The Tandem method has advantages and disadvantages when compared to the traditional method. The main advantage is the possibility of use of standard tandem accelerators to measure σ^d_0 at energies up to the maximum terminal voltage times the electron charge. At UFRJ 1.7 MeV is our energy limit. However, there are open laboratories currently operating tandems (with gaseous strippers) up to 20 MV (Fig. 1). A second crucial characteristic of the Tandem method is that relatively small analyzing magnets can be used, even for collision of very heavy projectiles at the highest available energies. This happens because after the collision at the center of the accelerator, the anionic beam is decelerated down to its injection energy (typically tens of keV) and can be easily bent to be detected by a Faraday cup. The outgoing neutral projectile is simply detected (through secondary electron emission) at the central exit of the magnet. The main disadvantage of our method is that negative and neutral detection necessarily have distinct collection efficiencies and beam transmission due to different focusing conditions by the accelerator itself. Thus, we do have beam transmission and detection efficiencies different from 100% [13]. However, these unknown values are not necessary for the determination of the destruction cross-sections σ^d. We do not need to know the beam transmission, it is sufficient to guarantee that (for each terminal voltage) the transmission is constant during a single measurement (while we vary the pressure at the gas stripper). The determination of absolute values for σ^d is possible, in the high-velocity limit, because these parameters appear in the arguments of exponentials (see Section 2.1). Positive outgoing projectiles can, in principle, be detected in a separate run but that would require a strong magnet, since cations are accelerated in the second accelerator stage. Under these conditions we cannot determine the cross-sections for electron loss to a particular final charge state. A quantitative assessment of the proposed method is presented in the rest of this section.

For a gas target with a finite thickness, the emerging beam fractions, F_i, satisfy the Allison's equations [10]

$$\frac{\mathrm{d}F_i}{\mathrm{d}x} + F_i\sigma^d_i = \sum_{j\neq i}^{N} \sigma_{ji}F_j \quad \text{with } \sigma^d_i = \sum_{j\neq i}^{N} \sigma_{ij}. \tag{1}$$

The set of coupled differential equations above can be transformed into a set of linear algebraic equations through the substitution

$$F_i(x) = F_{\infty i} + \sum_{k=-1}^{N} A_{ik}\exp(-s_k x). \tag{2}$$

This system can in principle be solved with the constants $F_{\infty i}$, A_{ik} and s_k expressed as functions of the cross-sections σ_{ji}. However, the expressions are cumbersome and fluctuations in experimental data for $F_i(x)$ make data reduction not straightforward in the determination of the σ_{ji} from fitted $F_{\infty i}$, A_{ik} and s_k, even for projectiles with only two electrons [10,16–18]. Important simplifications apply in the high-velocity regime.