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Charge-changing ion–ion collisions in heavy ion fusion

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Abstract

In heavy ion fusion, the compression of the DT pellet requires high intensity beams of ions in the gigaelectron volt energy range. Charge-changing collisions due to intrabeam scattering can have a high impact on the design of adequate accelerator and storage rings. Not only do intensity losses have to be taken into account, but also the deposition of energy on the beam lines after bending magnets, for example, may be nonnegligible. The center-of-mass energy for these intrabeam collisions is typically in the kiloelectron volt range for beam energies in the order of several gigaelectron volts. In this article, we present experimental cross sections for charge transfer and ionization in homonuclear collisions of Ar^{4+}, Kr^{4+}, and Xe^{4+}, and for charge transfer only in homonuclear collisions of Pb^{4+} and Bi^{4+}. Using a hypothetical 100-Tm synchrotron as an example, expected particle losses are calculated based on the experimental data. The results are compared with expectations for singly charged Bi^{+} ions, which are usually considered for heavy ion fusion.

Keywords: Charge transfer; Heavy ion fusion; Ionization

1. INTRODUCTION

The Heavy Ion Driven Inertial Fusion (HIDIF) layout (Hofmann & Plass, 1998) uses a RF linac/storage ring approach to heavy ion fusion with intense beams of 10 GeV Bi^{+} ions. While for such a low charge state, space-charge effects are minimal, charge-changing collisions leading to ion loss are of concern. Melchert *et al.* (1989) have shown for Bi^{+} that these losses, while small, are by no means negligible.

To improve driver efficiency, higher charge states are also discussed (Bongardt, 2001). In the past decades, however, the experiments on charge-changing homonuclear ion–ion collisions concentrated mainly on collisions involving singly or at most doubly charged ions (see bibliography by Tawara, 1983). Using the Giessen ion–ion *crossed-beams* setup, we have recently investigated charge transfer

$$X^{4+} + X^{4+} \rightarrow X^{3+} + X^{5+} \tag{1}$$

[where X = Ar, Kr (Diehl *et al.*, 2001), Xe, Bi (Trassl *et al.*, 2001), and Pb] and ionization

$$X^{4+} + X^{4+} \rightarrow X^{4+} + X^{5+} + e^{-} \tag{2}$$

[where X = Ar, Kr, and Xe (Diehl *et al.*, 2001)] for fourfold charged ions.

2. EXPERIMENTAL RESULTS

The Giessen ion–ion *crossed-beams* setup has been described in full detail by Meuser *et al.* (1996) and by Melchert and Salzborn (1999). The charge transfer cross sections σ_c shown in Figure 1 have been obtained using the coincidence technique. The experimental cross sections for Pb^{4+} and Bi^{4+} do not differ much, whereas the cross sections for the noble gases are significantly higher. As the collision velocity is much smaller than the Bohr velocity of the active electron, an increase of the cross section with energy is expected in these nonresonant collision systems. This is clearly shown by the calculations of Shevelko (2000), which are also shown in Figure 1. Apart from Ar^{4+} and Kr^{4+}, however, the measured cross sections show no obvious dependence on the collision energy. This may be due to the presence of metastable ions produced in the ECR–ion sources. Metastable ions will increase the charge exchange cross section at small energies, which also may partially explain the difference between experiment and theory. However, the fact that the experimental data for Bi^{4+} actually crosses the theoretical curve, with the experimental cross section being smaller at higher energies than the theoretical one, clearly shows the severe difficulties in a theoretical

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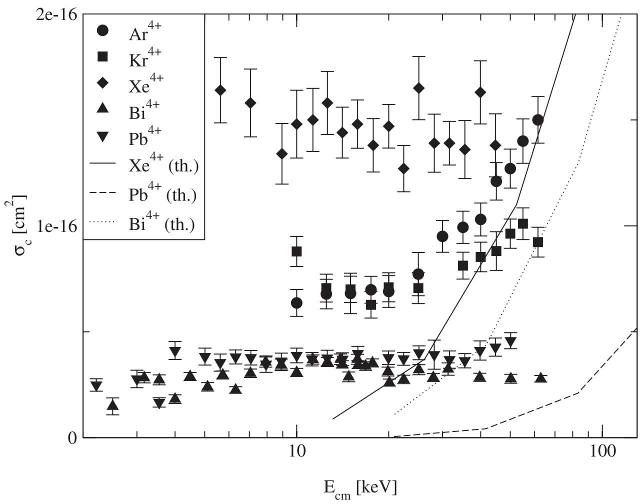

Fig. 1. Measured total charge transfer cross sections (Diehl *et al.*, 2001, Trassl *et al.*, 2001) and theoretical predictions by Shevelko (2000). The error bars indicate the statistical error only.

description of charge transfer for these heavy, many-electron systems.

Figure 2 shows the measured ionization cross sections σ_I. Here the beam pulsing technique rather than the coincidence technique was applied for signal recovery. This resulted in a larger background contribution and consequently larger error bars. For Xe^{4+}, a clear threshold behavior followed by a strong increase of the cross section with energy is observed. Most importantly, the ionization cross section exceeds the charge exchange cross section already a few kiloelectron volts above the threshold. For Kr^{4+}, no such behavior is seen and the ionization cross section is approximately equal to the charge exchange cross section. Nothing definite can be said concerning the influence of metastable ions.

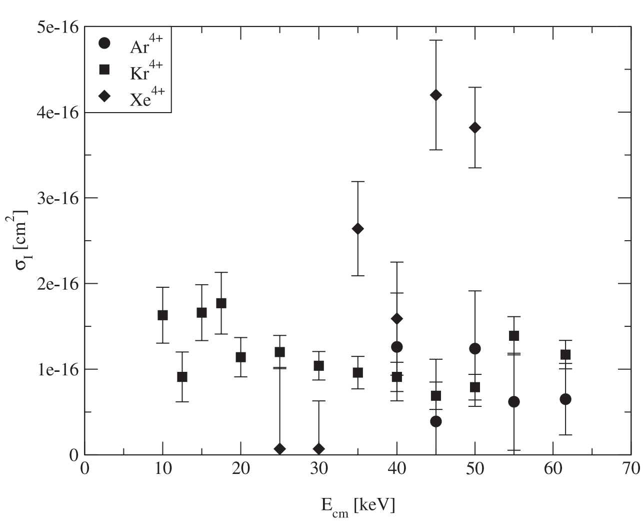

Fig. 2. Measured total ionization cross sections (Diehl *et al.*, 2001). The error bars indicate the statistical error only.

3. APPLICATION TO PARTICLE LOSSES IN A STORAGE RING

Based on the measured cross sections, expected particle losses can be estimated. Given a particle density distribution $n(r,t)$, the reaction rate $R(t)$ due to intrabeam scattering can be calculated by

$$R(t) = \frac{1}{2}\int_V n^2(r,t)\langle\sigma_L v\rangle\, dV, \tag{3}$$

with the rate coefficient

$$\langle\sigma_L v\rangle = \int \sigma_L(E) v f(E)\, dE, \tag{4}$$

where $f(E)$ is the energy distribution of the ions. The total loss cross section σ_L is given by

$$\sigma_L = 2(2\sigma_c + \sigma_I). \tag{5}$$

The factor 2 arises from the fact that in the capture reaction, both ions change their charge state and that both ions act simultaneously as projectile and target. Due to the difficulty in measuring the ionization cross section and based on measurements with Bi^{+} by Melchert *et al.* (1989), previous estimates of particle losses for Bi^{4+} and Xe^{4+} by Trassl *et al.* (2001) have been performed under the assumption that an upper limit can be obtained by setting the ionization cross section equal to the charge exchange cross section. As the measured cross section for Xe^{4+} shows, this approximation may not be adequate.

In Figure 3 we show the expected particle losses as a function of energy for a hypothetical 100-Tm storage ring with parameters as given in Table 1. In the calculations we have used the two approximations. The beam density is

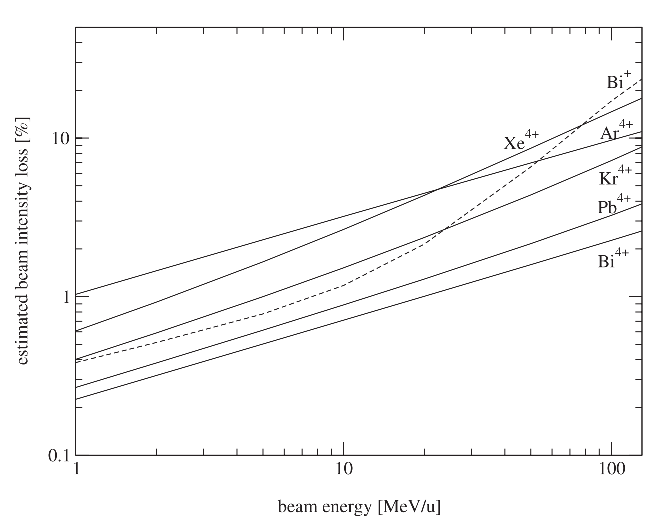

Fig. 3. Expected particle losses in a 100-Tm storage ring after 1 s storage time as a function of beam energy at a fixed emittance.

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Table 1. *Parameters used in the estimation of the expected beam losses*

Ring radius R	127 m
Bunching factor b	0.5
Storage time	1 s
Betatron oscillations Q	12
Emittance ϵ_{rms}	12π mm mrad
Number of ions N	8×10^{12}
Maximum energy E	127 MeV/u

assumed to be uniform: $n(r,t) = n(t) = N(t)/V$, where $N(t)$ is the total number of stored ions and V the beam volume. Based on a Monte Carlo simulation by I. Hofmann (pers. comm.), the rate coefficient is approximated by

$$\langle \sigma_L v \rangle = (1.8\sigma_0 + 4\sigma_1 v_{rms} + 11\sigma_2 v_{rms}^2) v_{rms}, \tag{6}$$

with

$$v_{rms} = \frac{1}{2}\beta\gamma c\sqrt{\epsilon_{rms}\frac{Q}{R}}. \tag{7}$$

The coefficients are obtained by fitting the total loss cross section with a second-order polynom. Furthermore, only the capture cross section has been taken into account for Pb^{4+} and Bi^{4+}. This means that the expected losses for these ions are a lower limit only. Also shown for comparison is the expected loss for Bi^{+} ions based on the charge transfer and ionization cross sections by Melchert *et al.* (1989). These cross sections increase with energy and show no indication of metastable ions. This results in the small expected loss for low beam energies, where the cross sections for fourfold charged ions are quite high. For high energies, however, the cross sections for singly charged ions dominate, resulting in a higher particle loss.

As can be seen from our data, beam losses due to intrabeam charge exchange cannot be neglected for low charged ions. In addition, even at the relative low energies involved, ionization may play an important role.

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