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Charge-state distribution and electron-loss collisions of ^{127}I ions in a tandem accelerator

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Abstract. The charge-state distribution of ^{127}I ions at the gas stripper of a tandem accelerator was measured for a wide range of charge states. When highly-ionized charge states were tuned, it was possible to identify spurious charge states originated in electron-loss collisions of the accelerated ions and the residual gas molecules within the accelerator tube. The rate of these spurious charge states were quantitatively analyzed and compared with calculations which take into account its tuning through the accelerator and cross sections for multiple-electron-loss atomic collisions.

Keywords: charge-state distribution, gas stripper, atomic collision
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1. Introduction

The charge-exchange collisions between energetic ions and material media, such as foils or gas cells, are of interest both for understanding the atomic properties involved and for the design and operation of facilities like tandem accelerators, in which the charge-state distribution at the stripper must be known [1–3]. On addition, electron-loss collisions may produce interfering ions which may constitute a severe background for extremely-low-intensity beams, as it is usual in accelerator mass spectrometry (AMS) experiments.

In this work we measured the charge-state distribution (from q=4 to q=19) of ^{127}I ions accelerated by a 8 MV terminal voltage and ionized by a gas stripper at

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the TANDAR accelerator [4]. When measuring high charge states, the presence of charge states different than the one tuned was explained in terms of collision of the accelerated ions with the molecules of residual gas within the accelerator tube. The measured rate of these spurious charge states was compared to calculations that take into account the cross sections for multiple-electron-loss atomic collisions. It is worthwhile to notice that, although both issues responds to the same physical process, we treat them differently due to their different regimes. The areal density of the gas stripper (of about 10^{17} molec/cm^2) implies a number of the order of 10^3 atomic collisions, in which the ion gains or loses electrons. Hence the charge-state distribution corresponds to the equilibrium one and its values are estimated by means of purely empirical formulae [5]. In contrast, the whole high-energy side of the accelerator tube (with vacuum values in the order of 10^{-7} Torr) has a gas areal density of about 10^{13} molec/cm^2, which makes the collision probability of about 10^{-2} and the probability of two collisions negligible. Hence, appearing spurious charge states can be analyzed in terms of well-determined single collisions in which one or more electrons are lost.

These new data complement similar measurements done with ^{35}Cl [1]. ^{127}I and ^{35}Cl (stable isotopes of radioactive ^{129}I and ^{36}Cl, respectively) are of particular interest for AMS.

2. Multiple-electron-loss processes

Single-electron-loss cross sections can be calculated using the binary-encounter approximation developed by Gryzinski [6]. In this model, the cross section $\sigma(v_i)$ for the ionization of an electron is calculated from an approximate expression for the two-body Coulomb-scattering cross section $\sigma(v_i, v)$, isotropically averaged over the directions of the velocities of the incident ion (v_i) and that of its orbital electron (v). Using an isotropic-hydrogenic density distribution for closed shells

$$\rho(v, v_j) = \frac{8}{\pi^2} \frac{v_j^5}{(v_j^2 + v^2)^4}, \tag{1}$$

where $\frac{1}{2} m_e v_j^2 = -U_j$, being U_j the binding energy of the j^{th} electron, the cross section $\sigma_j(E_i)$ for the individual ionization of the j^{th} electron of an ion incident on a target atom with atomic number Z_T can be integrated as

$$\sigma_j(E_i) = \int_0^\infty \sigma(v_i, v)\rho(v, v_j) 4\pi v^2 dv = \frac{\pi e^4 (Z_T^2 + Z_T)}{U_j^2} G(V). \tag{2}$$

Here , $V = v_i/v_j$ is the scaled velocity and $G(V)$ a function which accounts for the velocity-matching condition whose analitical expression is given in reference [7].

In order to calculate multiple-electron-loss cross sections, the cross section for ionizing the j^{th} electron is rewritten as a probability, as prescribed by Kessel [8]:

$$P_j(b, E_i) = \begin{cases} \frac{\sigma(E_i)}{\pi R_j^2} & \text{for} \quad b \leq R_j, \\ 0 & \text{for} \quad b > R_j, \end{cases} \tag{3}$$

where b is the impact parameter and $R_j \leq \sqrt{2}a_j$, being a_j the orbital radius of the j^{th} electron. Here the equality holds when $v_i = vj$. Under this approximation, the probability of ionizing the $j_1, ..., j_m$ electrons becomes

$$P_{j_1,\ldots,j_m}(b, E_i) = \begin{cases} \prod\limits_{\mu=j_1,\ldots,j_m} P_\mu \prod\limits_{\nu\neq j_1,\ldots,j_m} (1 - P_\nu) & \text{for} \quad b \leq R_{\min}, \\ \\ 0 & \text{for} \quad b > R_{\min}, \end{cases} \tag{4}$$

with $R_{\min}$=min$\{R_{j_1}, ..., R_{j_m}\}$. Hence, the cross section $\sigma^m(E_i)$ for an ionization of multiplicity m is calculated summing up all sets of m electrons, between the initial charge state q_i and the atomic number Z.

$$\sigma^m(E_i) = \pi \sum_{j_1=q_i}^{Z} \sum_{j_2=j_1+1}^{Z} \cdots \sum_{j_m=j_{m-1}+1}^{Z} R_{\min}^2 P_{j_1,\ldots,j_m}(E_i). \tag{5}$$

3. Tuning of spurious charge states

In a tandem accelerator, tuned ions with charge state q gain an energy of $E = e[V_P + V_T(1+q)]$, where V_P and V_T are the pre-acceleration and terminal voltages, respectively. However, if an ion undergoes a charge change $q_i \to q_f$ within the high-energy side of the accelerator tube, at a distance x from the stripper, the energy gained would be

$$E_{q_f}(x) = e\left\{V_p + V_T\left[1 + q_i\frac{x}{l} + q_f(1 - \frac{x}{l})\right]\right\} \tag{6}$$

where l is the electrically active length of the high-energy side (l=12 m in our case). In order to be accepted by the analyzing magnet, set to tune a charge state q_0 with an energy E_0, an isobar ion with spurious charge state q_f must achieve the same magnetic rigidity, i.e.: $E_{q_f}/q_f^2 = E_0/q_0^2$. Moreover, the length Δx of the region (centered at x) in which the collision should occur is determined by the acceptance of the analyzing magnet ($\Delta\rho/\rho = 7\times10^{-3}$ in our case). Hence, from the relationship $B\rho = p/q$ and eq. (6)

$$\Delta x = \frac{l\Delta E_{qf}}{V_T|q_i - q_f|} = \frac{2lE_{qf}}{V_T|q_i - q_f|}\frac{\Delta\rho}{\rho} \tag{7}$$

This region acting as a gas-cell target can be as long as 1 meter, and if it includes a dead section (in the case of the TANDAR accelerator there are two, 60 cm long each) its length is added to Δx.

The ionization probability at the position x is proportional to the local density of the gas δ and to the cross section for the ionization process $\sigma(E_i, q_i \to q_f)$, which in turn depends on the energy of the incident particle E_i at that position. The number of ions having a given charge state q_i is $F(q_i)It/e$, where $F(q_i)$ is the charge-state fraction emerging from the stripper corresponding for the ionic state q_i, I is the beam current at the high-voltage terminal Faraday cup, and t is the measuring time. Therefore, the number of detected particles with charge state q_f stemming from those ionizing reactions, $N(q_f)$, can be expressed as

$$N(q_f) = \frac{I}{e} tT\delta \sum_{q_i} F(q_i)\sigma(E_i, q_i \to q_f)\Delta x(E_{qf}, |q_i - q_f|) \tag{8}$$

where T is the beam transmission from the stripper to the detector. Here the sum runs over those initial charges q_i fulfilling the acceptance condition of the analyzing magnet for any $0 < x \leq l$. In most cases these initial charges must fulfill $q_i \leq q_f - 2$, i.e. only multiple-electron loss collisions may contribute.

Charge states stemming from single-electron loss collisions have always a strictly higher magnetic rigidity than the tuned beam. However, in some particular cases, the single-electron loss collisions produced at the end of the accelerating tube may be accepted provided the image slit of the analyzing magnet is wide enough. In these cases, and in all in which collisions at $x = l$ are accepted, the length from the end of the accelerating region to the analyzing magnet (13 m in the case of the TANDAR accelerator), must be added to Δx, since in this region the ions energy remains constant. Thus, the intensity of these spurious beams is strongly enhanced.

It should be noted that ions having undergone a charge exchange in the low-energy side cannot be tuned and since there are no focusing elements in the high-energy side of the accelerator, it is assumed that the transmission T does not depend on the charge state. In order to circumvent absolute transmission and current uncertainties, the number of detected particles $N(q_f)$ is normalized to the number of events of the tuned charge state $N(q_0) = F(q_0)ItT/e$ and expressed as a relative yield

$$Y(q_f, q_0) = \frac{N(q_f)}{N(q_0)} = \frac{2l\delta}{V_T F(q_0)} \frac{\Delta\rho}{\rho} \sum_{q_i} F(q_i)\sigma(E_i, q_i \to q_f) \frac{E_{qf}}{|q_i - q_f|} \tag{9}$$

4. Experiments

Abundant charge states ($4 \leq q_0 \leq 12$) were measured at a Faraday cup after the analyzing magnet, optimizing the beam intensity for each state. Charge states between 11 and 19 were measured with a $\Delta E - E_{residual}$ detector, through an elastic scattering on ^{197}Au foils as attenuation method. Weaker charge states can be directed without attenuation into the detector. For charge states $q \geq 13$, no current was measured at the Faraday cup and the beam optimization was not possible. Hence, field values for the magnet and focusing elements were extrapolated from those of the abundant charge states. Also, the regulation of the terminal voltage can not be done in the slit mode and the generating voltmeter (GVM) must be used. Fig. 1 shows the measured charge-state distribution, compared with a χ^2 distribution with a mean value $\bar{q}$ = 4.15 and a width of d=1.96, calculated from the empirical formulae of ref. [9] and [5], respectively. Fig. 2 shows a typical $\Delta E - E_{residual}$ spectrum recorded when a weak charge state (q_0=17) was tuned. It can be seen that spurious charge states q_f=10–16 having comparable intensities could be clearly separated. Fig. 3 shows a comparison between measured and calculated relative yields for q_0=17, as defined in eq. (9). For the evaluation of eq. (9), the measured values for the charge-state distribution $F(q_i)$ were used. Due to the complexity of calculations, and the roughness of the approximations made, only an agreement in the order of magnitude is aimed.

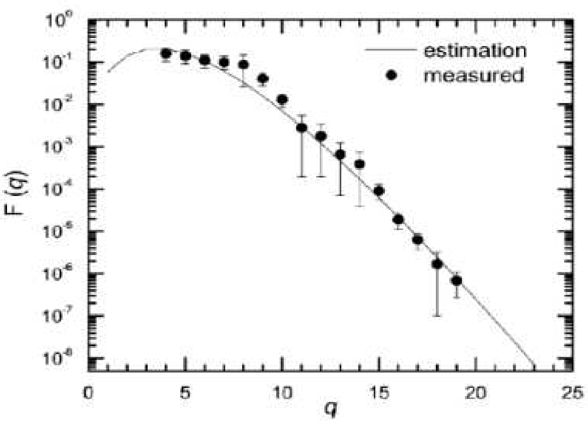

Fig. 1. Charge-state distribution of 8 MeV ^{127}I ions at a 10^{17} molec/cm^2 gas stripper. The circles represent measured values and the line an estimation based on empirical formulae of ref. [9] and [5].

5. Conclusions

The charge-state distribution of ^{127}I ions in a gas stripper was measured and the spurious charge states which can become an interference in AMS measurements were quantitatively analyzed. The agreement in the order of magnitude between estimated and measured relative yields supports the hypothesis that these spurious charge states are originated in collisions with the residual gas in the accelerator.

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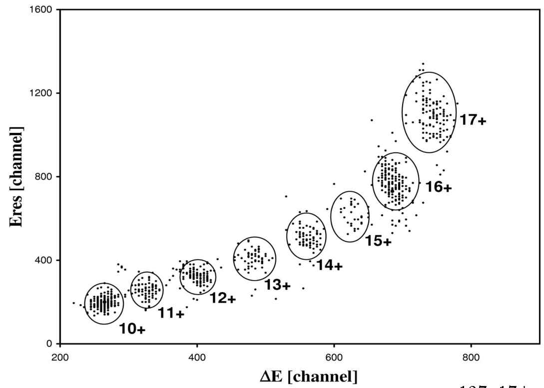

Fig. 2. $\Delta E - E_{residual}$ spectrum recorded while tuning $^{127}I^{17+}$ ions. Spurious charge states q_f=10–16 stemming from electron-loss collisions and having the same magnetic rigidity can be clearly identified.

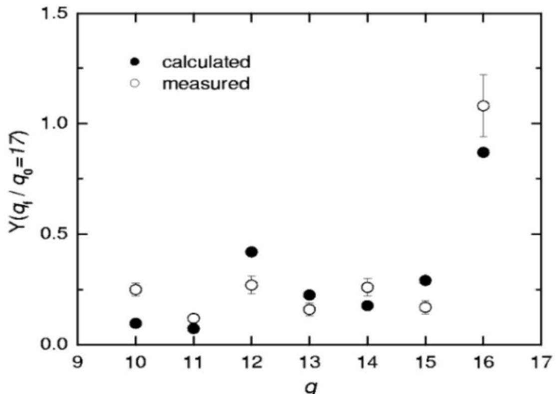

Fig. 3. Relative yields $Y(q_f, q_0 = 17)$, as defined in eq. (9). The solid circles indicate the calculated values and the open circles the measured ones.

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