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Measurement of the transverse kinetic energies of argon recoil ions produced in 120 MeV Si^{8+}–Ar collisions

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Abstract. Measurements were carried out to deduce the transverse kinetic energies of highly charged argon recoil ions produced in single collisions of 120 MeV Si^{8+} ions with argon atoms in which the post collision charge states of the projectiles were not determined. A time of flight spectrometer was designed and fabricated to detect the charge states of recoils. Experimental procedures for optimizing the spectrometer for extraction, transmission and detection of recoils are described. A simple approach for determining the transverse kinetic energy of the recoil ions from FWHM of the peaks is reported. This method is shown to be independent of the choice of collision partners and requires only the knowledge of the physical values of "optimized parameters" of time-of-flight spectrometer used in the experiment. The transverse kinetic energy of the recoil ions determined from the present approach is found to vary from 0.03 eV for Ar^{+} to 4.02 eV for Ar^{10+}. These values are compared with the results reported by earlier workers and are shown to follow a q^2-behaviour up to a charge state $q = 8+$ of the recoil ions.

PACS. 07.75.+h Mass spectrometers and related techniques – 07.81.+a Electron, ion spectrometers, and related techniques – 34.50.Fa Electronic excitation and ionization of atoms (including beam-foil excitation and ionization)

1 Introduction

When a fast moving heavy ion (few MeV/amu) interacts with a neutral gaseous target atom, many electrons from the target atom are ejected out. Such an event causes the production of an "electronically-hot" but "translationally-cold" recoil ion [1]. The physics of such recoil ions has been the focus of many studies during the past few years. Atomic processes involving these recoil ions play an important role in various fields, such as, precision wavelength spectroscopy, fusion plasma studies [2], study of the static and dynamic behaviour of the star atmospheres and development of VUV and X-ray laser systems [3].

In 1976, Mann *et al.* [4] experimentally verified that recoil ions had small translational energies. The first direct electrostatic measurements of recoil energies did not appear until the measurements of Ullrich *et al.* [5–7] and of Levin *et al.* [8]. Investigations on the mean kinetic energies and the angular distributions of the primary recoils studied using the time of flight [TOF] technique have been made subsequently by several workers [9–12]. Recent advances in experimental technique called "cold target recoil ion momentum spectroscopy" (COLTRIMS) have allowed for measurement of the transverse and the longitudinal components of momentum of the recoiling target emerging from an ionizing collision of an atom with an impact of a radiation. Using a classical TOF technique, Grandin *et al.* [13] have determined the mean recoil kinetic energies of highly charged neon and argon ions produced in 27.0 MeV/amu Xe^{52+}–Ne, Ar collisions. It is pointed out that in such a swift heavy ion-atom collisions under specific conditions, the shape of charge state characteristic peaks provided by TOF spectrometers reflects directly the distribution function of the recoil ion velocity components along the extraction axis of the spectrometer. Hence, the values of mean kinetic energy of recoil ions from TOF peaks of relatively higher charge states which sufficiently exceed thermal energy can be readily deduced. However, taking into account the inelasticity related to the ionization of the target atom, the angle of emission of recoils may be notably different from 90°.

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With a view to check the validity of the two-body collision model, Jardin *et al.* [14] have measured the three components of the target velocity in 6.7 MeV/amu Xe^{44+}–Ar collisions. Three components of the velocity of target ion of mass m, V_x, V_y, and V_z were measured considering the parallel momentum component $P_{R||} = mV_x$ and the transverse component $P_{R\perp} = m\sqrt{(V_y^2 + V_z^2)}$ with respect to the projectile direction taken along x-axis. They have shown that the argon recoil ions are emitted in the backward direction with respect to the projectile beam direction while the electrons are preferentially ejected in the forward direction. They could achieve this information by using a high resolution recoil ion momentum spectrometer consisting of a two-dimensional position sensitive microchannel plate and a supersonic gas jet of target atoms with a very low velocity spread along jet direction (about 7 K). Further, they have concluded that the interaction between the projectile and the ejected electrons on one hand and the interaction between the projectile and the target on the other hand may not be considered as independent quantities. As a result, the two-body collision model may underestimate the kinetic energy deposited on the target nucleus. A similar result has also been reported by Unverzagt *et al.* [15] in their studies of the collective behaviour of ejected electrons in multiply ionizing collisions of 5.9 MeV/amu U^{65+} + Ne. A detailed review by Ullrich *et al.* [16] gives a deeper insight into the advantages of COLTRIMS technique for studying the dynamics of such ion-atom collisions.

In a TOF spectrum of the recoil ions recorded under an optimized time focusing condition with a negligible electronic contribution to the time resolution, the full width at half maximum (FWHM) of the recoil peaks will be determined by the distribution of translational kinetic energies given to the recoil ions in the primary collisions. If the recoils are created with equally weighted azimuthal angles and are translated at 90° to the projectile beam direction, the width of the time peak can be given by [10],

$$\langle (t_0 - t)^2 \rangle = mE/(qe\varepsilon)^2 \quad (1)$$

where E is the mean initial kinetic energy of the recoil ions of mass m and charge state q in the interaction region; t_0 and t are the times of flight of the recoils from the interaction region to the detector with $E = 0$ and $E \neq 0$ respectively and ε is the field of extraction of a recoil-ion from the interaction region. For a given charge state q of a recoil ion, Levin *et al.* [8] deduced E from a fit of the FWHM data to the following expression without having the necessity of an exact time-focusing condition,

$$\langle (t_0 - t)^2 \rangle = \alpha + \beta/q\kappa + \gamma/(q\kappa)^2 \quad (2)$$

where the constants α, β and γ represent the contributions from the intrinsic time resolutions of the detector and that of the pulsed beam width, flight variations due to fringing fields and the contribution from the recoil energies respectively. The parameter κ is proportional to the the electric field strength. Heber *et al.* [11], in the studies of argon recoils produced in 96 MeV Ar^{4+} and Ar^{15+} ions on argon atoms parametrized the squared of FWHM of the recoil peaks as the sum of the squares of the contributions from the intrinsic time resolution and from the time spread due to space and kinetic energy distributions. They deduced the average impact parameters from the energies of the argon recoils which are found to vary from a few hundreths of an eV for Ar^+ to over 5.0 eV for Ar^{11+}. Watson *et al.* [12] quote an average recoil energy of 0.16 eV for Ar^+ recoils produced in 40 MeV Ar^{13+}–Ar collisions.

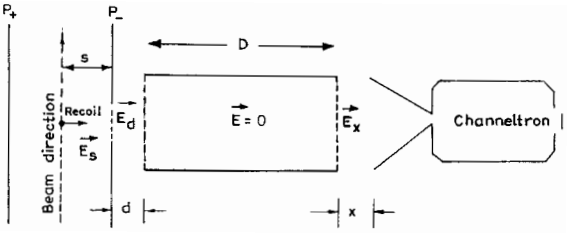

Fig. 1. Schematic diagram of the time of flight setup. Symbols are described in the text.

In order to perform a systematic study of the various physical mechanisms leading to the production of the recoil ions, a new experimental set up called SCORPION (System for Coincidences between Recoil and Projectile IONs) consisting of a time-of-flight spectrometer and a charge state analyzer was developed at the Nuclear Science Centre (NSC), New Delhi [17]. Various tests related to the optimization of the spectrometer's extraction, transmission and detection of the recoil ions were performed. This set up was then used to study the production of the recoil ions in the collision of neutral argon atoms with 120 MeV Si^{8+} ions. The transverse kinetic energies of the recoils were deduced from the half intensity width (FWHM) of the peaks in the TOF spectrum and the values were compared with the results reported by earlier workers.

2 Experimental set-up

The measurements were performed in the General Purpose Scattering Chamber (GPSC) [17] facility of NSC with the time-of-flight spectrometer mounted inside. The spectrometer is a SS chamber with a provision for gas inlet through a hypodermic needle, adjustable collimators for defining the beam path and a time of flight setup. There is a provision for the rotation as well as for translation of the spectrometer in the horizontal and vertical planes. A diffstack pump with a speed of 2000 l/s was used to evacuate the GPSC, while a separate diffusion pump with a speed of 200 l/s placed below the spectrometer, was used to pump out the target gas. These pumps maintained a base pressure of better than 1×10^{-6} torr in the GPSC.

The TOF set up was placed at 90° to the projectile beam direction in a horizontal plane. A schematic diagram of the set up is shown in Figure 1. P_+ and P_- are two copper plates spaced 20 mm apart across which a field E_s is applied. P_- has a 5 mm hole in its centre over

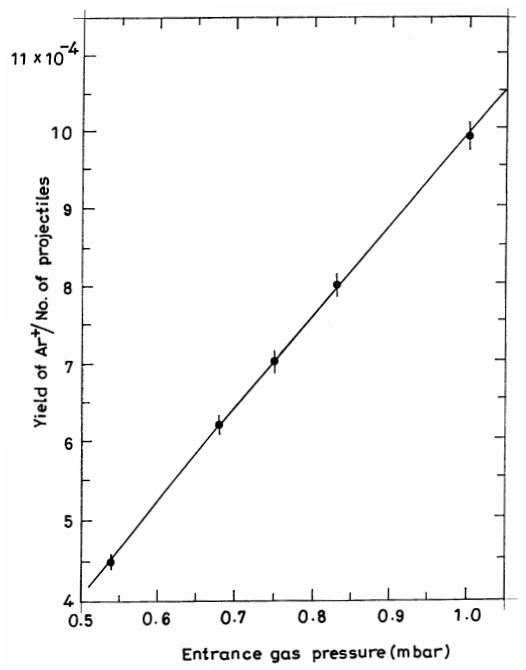

Fig. 2. Yield of the Ar^+ recoil ion normalized to the number of projectiles plotted as a function of the argon gas pressure. Solid line is a straight line fit to the data.

which a grid of 25 μm wires spaced 1 mm apart is epoxied using a conducting glue. A 30 mm long drift tube is placed 3 mm away from P_-. The two ends of the drift tube are covered with a grid of parallel wires having identical transmission as mentioned above. Following the drift tube, a channeltron detector with no position information was placed 5 mm away from the former. Target gas was fed into the interaction region at a room temperature through a hypodermic needle (0.5 mm diam.) which was connected to a gas handling system through a nalgene tubing. The flow of the gas was adjusted using a fine needle valve to achieve a pressure of about 1×10^{-5} torr and was monitored by a Penning gauge placed at a distance of 200 mm below the interaction region. The single collision condition was ensured by examining the reaction rate of argon with gas pressure as shown in Figure 2. Over a wide range of pressures, the obtained charge state fraction is seen to increase linearly with gas pressure within the experimental uncertainty.

A pulsed 120 MeV $^{28}Si^{8+}$ beam with a repetition rate of 1 μs provided by the 15 UD Pelletron accelerator was used to bombard the gaseous argon atoms. The beam diameter in the interaction zone was estimated to about 3 mm. Fine tuning of the beam direction was found to be useful to maximize the yield of the recoil; this ensured that the beam is properly centered. Recoil ions produced in the interaction region are extracted by the field E_s (Fig. 1). Following acceleration by the field E_d between the plate and the drift tube, the ions drift through the potential V_D. They are finally detected in the channeltron after post acceleration due to the field E_x between the drift tube and the detector. The timing signal was derived from the channeltron using a fast current sensitive preamplifier. The rise times of the observed pulses were found to be less than a nano-seconds. Signals from the channeltron and that from the rate divided RF were used to start and stop the time-to-amplitude converter (TAC) respectively. Output signals from the TAC provided the required time of flight spectrum of the argon recoil ions. It may be pointed out here that it was not possible for us to resolve the parallel and the transverse components of momentum of recoils by the present setup. The results presented for initial kinetic energy E should mean to refer to only the transverse components of the recoil ion's energy from here and onwards.

3 Optimization of the TOF spectrometer

A number of factors affect the ultimate time resolution of a TOF spectrometer; namely, intrinsic time resolution of the detector, width of the pulse beam time spread due to initial space resolution and initial kinetic energy distribution of recoil ions [19]. Contributions affecting the time-resolution stem mainly from the detector and width of the pulsed beam. These are accounted for as described in the Section 4. The time spread due to initial space distribution arises from the ions having the same mass to charge (m/q) ratio but the different positions in the interaction region defined by the overlap of the finite widths of the beam and that of the gas target. This spread can be reduced to a considerable extent by optimizing the voltages on the different electrodes of the spectrometer. The time spread due to kinetic energy distribution of ions arises due the ions having the same m/q ratio and the same birth place but possessing different velocities. Experiment were carried out not only to optimize the spectrometer for extraction, transmission and detection of recoil ions but also to minimize the time spreads due to initial space and kinetic energy distributions by following the similar procedures as given in [20]. SIMION code [21] helped in simulating the trajectories of the recoil ions in the time of flight setup used for an experiment.

The complete extraction of the recoil ions from the interaction region was ensured by studying the variation in the yield of 1^+ recoil ions normalized to the charge collected in the Faraday cup as a function of the voltage applied to the plates P_+ and P_-. The yield of the recoil ions was found to increase with the applied voltage and then to assume a constant value above $\pm$ 800 V. The choice of 1^+ charge state was based on the fact that it is the slowest moving ion in the process of extraction from the interaction zone to the detector.

Above a certain applied bias voltage, the channeltron is known to have an equal detection efficiency for all ions [22]. The optimum voltage for detecting all recoils in the interaction zone was determined by studying the variation in the charge state fractions of the recoil ions in 1^+ charge state normalized to the charge collected in the Faraday cup as a function of the voltage applied to the channeltron. For voltages larger than -2.1 kV, the yield was found to assume a constant value.

Table 1. Values of optimized distances and voltages for different components of the TOF spectrometer.

Distance of interaction. Point from P$_-$ (s)	10 mm
Distance of drift tube from P$_-$ (d)	3 mm
Length of the drift tube (D)	30 mm
Distance of the channeltron from drift tube (x)	5 mm
Voltage on P$_-$	−1.0 kV
Voltage on P$_+$	+1.0 kV
Voltage on the drift tube	−1.3 kV
Voltage on the channeltron mouth	−2.2 kV

The optimized distances and the corresponding voltages for different components of the TOF spectrometer are given in Table 1.

4 Calculations of the recoil energies

The recoil energies have been deduced from the FWHM (Γ) of the recoil ion peaks observed in the TOF spectrum. The contributions to the FWHM of the recoil peaks in a given charge state comes from the width of the pulsed beam (Γ_{beam}), the intrinsic time resolution of the detector (Γ_{det}), the time spread due to the space distribution of the ions (Γ_{space}) and from the time spread due to the initial kinetic energy distribution of ions (Γ_{KE}). Thus,

$$(\Gamma)^2 = (\Gamma_{beam})^2 + (\Gamma_{det})^2 + (\Gamma_{KE})^2 \tag{3}$$

Γ_{beam} and Γ_{det} are independent of the mass and charge state of the recoil ion under consideration, Γ_{space} is found to be proportional to $(m/q)^{1/2}$ while Γ_{KE} is proportional to $(mE/q^2)^{1/2}$ and is directly associated with equation (1). Hence equation (3) can be written in the form,

$$(\Gamma)^2 = A + B(m/q) + C(mE/q^2) \tag{4}$$

where, $A = (\Gamma_{beam})^2 + (\Gamma_{det})^2$ and E = mean kinetic energy of recoil ions.

The time resolution of the spectrometer for detected recoil ions is limited by variation of path length traveled by them to different distances on the channeltron cone which is usually not better than 20 ns. However, by a careful optimization of the spectrometer for (i) complete extraction of ions from a defined collision region, (ii) equal transmission for all recoils and (iii) for their equal detection probability under a single collision condition, it was possible to focus the recoil ions on the channeltron cone to within a distance of about 0.2 mm or better which corresponds to a time resolution of 3 ns for Ar^+ ions. This was supported and verified from simulation results of the recoil ion trajectories calculated by a SIMION code [21]. The overall time resolution of the present detection system as measured by the width of recoil ion peaks was about 6 ns. Taking the intrinsic time resolution of the channeltron to be 2 ns and the temporal width of the pulsed beam to be 5 ns, the parameter A was calculated using equation (4). Heber *et al.* [11] determined the value of "B" from the measured width of the TOF peak of He^+ by setting E in equation (4) equal to $(3/2)kT$. Here, the authors assumed the energy transfer to the He atoms to be much less than the thermal kinetic energy distribution in the target gas. Therefore, the dominant energy of the helium recoil is its thermal room temperature energy [23]. However, in a situation where He is not used as a target gas, the procedure adopted by Heber *et al.* may not be applicable.We have therefore adopted a general approach to calculate the parameter B. This approach requires no assumptions, rather it utilizes only the physical values of the optimized parameters of the TOF set up used as input. The parameter B is obtained from expression,

$$(m/q) = (\Gamma_{space})^2 = [(dT/ds)(\Delta s)]^2 \tag{5}$$

dT/ds refers to the variation in flight time due to the variation in s (the distance of the place of birth of the ion from the extractor plate) [19]. Δs refers to the maximum distance on either side of the interaction region where the ions may be born. In our case s has been taken to be equal to the radius of the projectile beam (*i.e.*, 1.5 mm). The value of dT/ds is obtained by substituting the values of various distances of the TOF setup and those of the accelerating fields in the equation:

$$\frac{dT}{ds} = \left(\frac{m}{q}\right)^{\frac{1}{2}} \left\{ \frac{2^{\frac{1}{2}}}{2} \left[\frac{1}{a^{\frac{1}{2}}} - \frac{sE_s}{2a^{\frac{3}{2}}} + \frac{E_s}{E_d}\left(\frac{1}{b^{\frac{1}{2}}} - \frac{1}{a^{\frac{1}{2}}}\right) - \frac{DE_s}{2b^{\frac{3}{2}}} + \frac{E_s}{E_x}\left(\frac{1}{c^{\frac{1}{2}}} - \frac{1}{b^{\frac{1}{2}}}\right)\right]\right\} \tag{6}$$

where, $a = sE_s$, $b = sE_s + dE_d$, $c = sE_s + dE_d + xE_x$.

The parameter C is calculated by considering the time spread due to the turn-around time between two ions born at the same position but with the velocity vectors pointing in opposite directions.

$$C(mE/q^2) = \text{Turn}-\text{around time} = 8(mE/q^2E_s^2). \tag{7}$$

On comparing the two sides of the equation (7), $C = 8/E_s^2$, where E_s is the field in the extraction region. Once the values of B and C are found out using equations (5) to (7), the value of E can be deduced from equation (4).

It may, however, be pointed out that the energies so deduced correspond to the value of one component of momentum of the recoil ions in a direction transverse to the beam. As stated earlier, gas was injected into the interaction region through a hypodermic needle. The target atoms were thus at a room temperature of 300 K. Also the recoil ion's detector used in the present experiment was not position sensitive; both these factors did not permit us to separate the longitudinal and the transverse components of the recoil ion velocity. Effectively, we have therefore measured only one component of the transverse momentum of recoil ions.

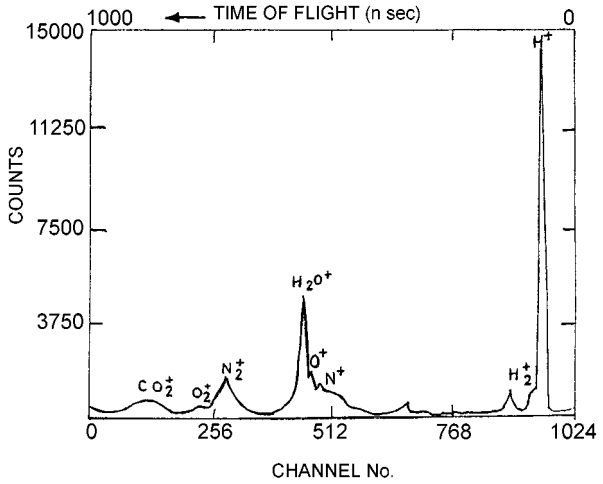

Fig. 3. Time-of-flight spectrum of the background recoils in 120 MeV Si^{8+} ions colliding with residual gases.

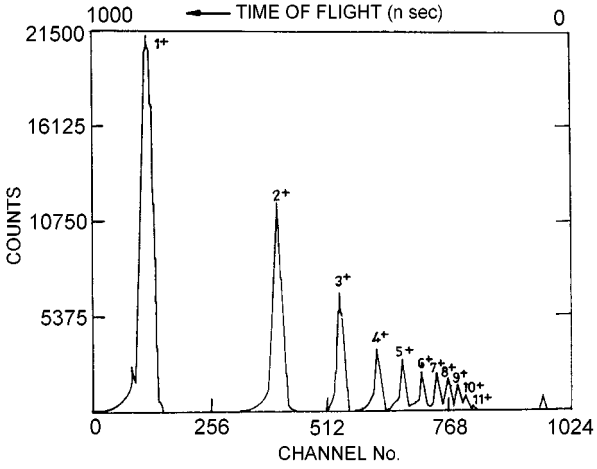

Fig. 4. The background subtracted time-of-flight spectrum of Argon recoils in 120 MeV Si^{8+}–Ar collisions.

5 Results and discussion

The total recoil ion spectrum has a finite contribution originating from the residual gas. A typical background spectrum of the recoil ions from the residual gas is shown in Figure 3. In the figure it is observed that the ions showing the prominent yields are H_2O^+, O^+, N^+, H^+, H_2^+ and CO_2^+. These ions have times of flight which are quite different from those of the argon recoils. Hence, they do not interfere with any of the argon recoil peaks under consideration. Also, the ratio of the yield of the ions from the residual gas (*e.g.*, H_2O^+, O^+, N^+) normalized to the number of projectiles was found to be constant with the increase in the argon gas pressure. This suggested the fact that the residual gas was present in the system as a constant background and that the argon gas used for the measurement was free from any contaminant gases (quoted purity of argon was 99.99%). A TOF spectrum of the argon recoils after appropriate subtraction of the background is shown in Figure 4. Recoils up to charge state 11^+ are obtained. The tailing observed in the recoil peaks of the lower charge states is due to the charge loss of the recoil ions in the flight path during interaction with the residual gas. The charge loss causes a slight change in the transit time of the recoils during the final acceleration in the channeltron cone. Recoil ion fractions were obtained by dividing the yield of the recoil ions in a given charge state with the yield for all the charge states. Uncertainties of the relative charge state fractions obtained in the experiment are estimated to range from 1% for Ar^+ to 36% for Ar^{11+}. Figure 5 shows the % fractions of the recoil ions obtained as a function of their charge states. It is seen that after the charge state 8^+ of the recoils, the fractions for the higher charge states drop suddenly. This is due to the "shell-effect" in argon caused by the sudden change in the binding energy of electrons in transition from M- to L-shell of the atom. Similar feature has also been observed by other workers [1,10].

The recoil energies obtained using equation (4), after subtraction of the contribution due to the thermal energy,

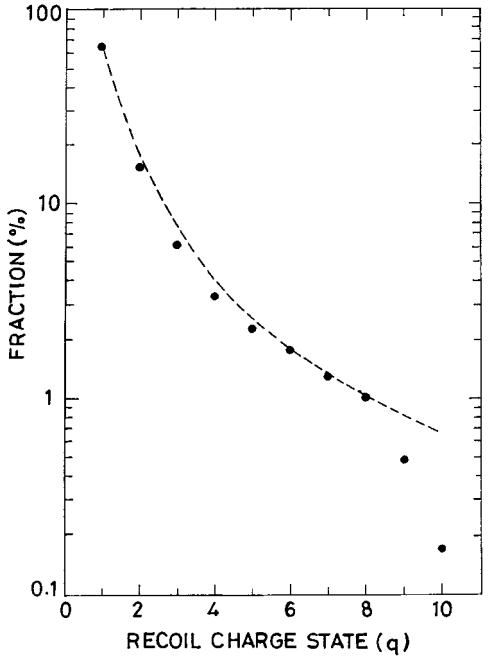

Fig. 5. Fraction of the recoils plotted as a function of the recoil ion charge state. Dashed curve represents a $1/q^2$ fit to the data points.

are found to vary from 0.03 eV for Ar^+ to 4.02 eV for Ar^{10+}. It may be pointed out that these energies correspond to the momenta gained by the recoil ions in the transverse direction with respect to the beam direction. These are plotted as a function of the corresponding recoil charge states in Figure 6. The error bars shown on the data points refer to the uncertainties in the determinations of the FWHM of the recoil ion peaks. Data by Heber *et al.* [11] for 96 MeV Ar^{15+}–Ar are also included in the figure for comparison. We note that in both the cases the variation of the recoil ion energy is similar in shape and magnitude. These observations lead to the conclusion that the kinetic energies of the recoils do not depend critically on the projectile's nuclear charge for the cases compared.

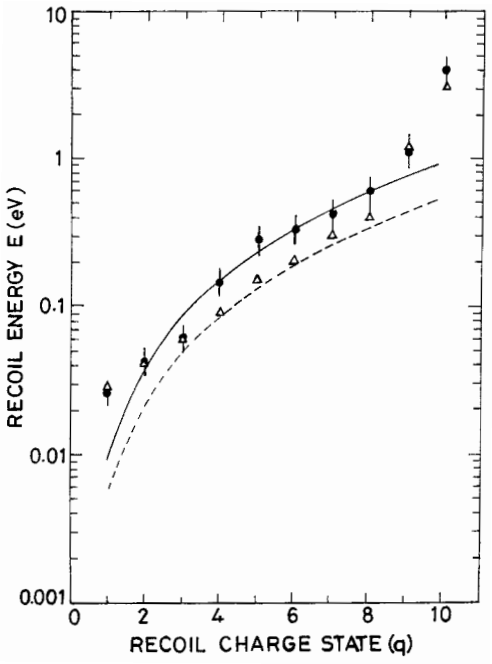

Fig. 6. Transverse initial kinetic energies of the argon recoils determined from the TOF peak width as a function of the recoil charge state in (•) 4.28 MeV/amu Si^{8+}–Ar (present data) and (△) 2.42 MeV/amu Ar^{15+}–Ar (Heber *et al.* [11]): dashed and full curves are the q^2 fits to the data normalized at $q = 6$ for Heber's and for the present data, respectively. Error bars on the Heber's data are similar to ours.

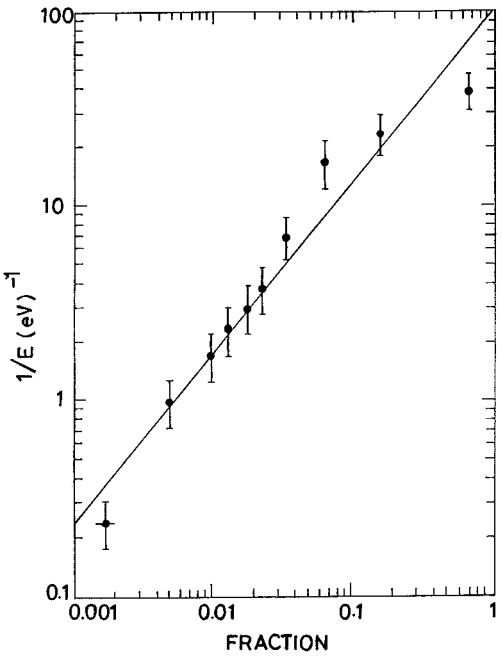

Fig. 7. Variation of the fraction of the recoil ions as a function of the inverse of the recoil energy. The solid line is a straight line fit to the data.

Additionally, as the projectile velocities in both studies are similar, the strength of multiple ionization of the target atom is expected to be nearly the same in both collision systems.

It is interesting further to compare the present results of transverse initial kinetic energies of argon target ions ionized by 4.3 MeV/amu Si^{8+} impact with those of argon ions produced by 6.7 MeV/amu Xe^{44+} ions (see Ref. [14]). Since it was not possible in the present work to resolve two components of the transverse momentum, namely, mV_y and mV_z, our results, therefore essentially refer to only one transverse momentum component (mV_z) of initial kinetic energy of the target ions; the mV_y component of the transverse momentum is however, not determined. From the work of reference [14], it is found that Ar^{q+} ($q = 1-7$) ions correspond to the mean initial kinetic energies E in the transverse directions to the projectile beam to be about 5 to 100 times higher than those of our present values, for example, for Ar^+ ions $E = 0.03$ eV (present) and 0.145 eV (Ref. [10]) and for Ar^{6+}, $E = 0.3$ eV (present) and 26.03 eV (Ref. [10]). This mismatch between two results may be considered due to the facts that (1) the projectile velocities in two cases are different (4.3 MeV/amu and 6.7 MeV/amu), (ii) only one velocity component is measured in the present experiment and (iii) the projectile ions used in our experiment are much lighter than those used in reference [14], causing different values of momentum transfer to the target atoms. These points if considered and accounted for, the two results are expected to come closer to an agreement.

Present results on the recoil energies are found to follow a q^2-behaviour. Deviations from this trend are observed for the lower and higher charge states of the recoils as noted by Heber *et al.* [11]. Assuming a projectile velocity to be appreciably greater than that of the target electrons, the expression for the recoil energy based on Olson's parametrization of the CTMC results [24] is given by the expression:

$$E(\text{eV}) = 4 \times 10^{-4} q^2 p^2 / M_r E_p b^2 \qquad (8)$$

where p is the projectile charge state, q is the charge state of the recoil ion, M_r is the mass of the recoiling ion, E_p is the projectile energy and b is the impact parameter. For given M_r, E_p and p, E follows a q^2-behaviour suggesting that the intermediate charge states of the recoil ions (up to 8^+) are born out of interactions taking place approximately within the same range of impact parameters, as it was also shown by Levin *et al.* [8]. In order to look for the dependence of the recoil energies on the charge state fractions, the latter were plotted as a function of the inverse of the recoil energy as shown in Figure 7. The variation of the recoil fraction with $1/E$ is seen to be linear for almost all the charge states. Consequently, the recoil fractions must also show a $1/q^2$-behaviour represented by the dotted curve in Figure 5. This dependence can be expected from the binding energy considerations. Further, the linear behaviour between fractions and $1/E$ is seen to be valid for the charge states 9^+ and 10^+ as well. This suggests that both, the energy and charge state fractions are affected to the same extent by the onset of L-shell ionization.

6 Conclusions

A time of flight spectrometer has been designed, fabricated and optimized for the recoil ion extraction, transmission and detection efficiencies. A general approach to calculate the transverse energies of the recoil ions from the FWHM of their peaks has been discussed. This method involves essentially the input of the experimental values of the distances and voltages of the TOF spectrometer for deducing the initial mean kinetic energies of the recoil ions. The energies calculated from the present approach are found to agree well with those reported by Heber *et al.* and to follow a q^2-behaviour up to a charge state of 8^+ of the recoil ions. This result points to the fact that for the intermediate charge states of the recoil ions, the impact parameter is hardly q dependent. The variation of the charge state fractions with $1/E$ is observed to be linear. This suggests that, for the collision system under study, the charge state and energy of the recoil ions are affected to almost the same extent for the M- as well as L-shell ionization. The low values of the recoil energies further suggest that the Doppler broadening of the spectral lines arising from such ions will be negligibly small and they can be used as a spectroscopic source for producing a discrete radiation.

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