Aust. J. Phys., 1988, 41, 681–92

# Excitation of Swift Heavy Ions in Foil Targets. IV* Preequilibrium Energy Losses and Mean Charge States

*L. B. Bridwell,[A] H. J. Hay, L. F. Pender,[B] C. J. Sofield[C] and P. B. Treacy*

Department of Nuclear Physics, Research School of Physical Sciences,
Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601, Australia.
[A] College of Health and Applied Science, Southwest Missouri State University,
Springfield, MO 65807, U.S.A.
[B] CSIRO Marine Laboratory, G.P.O. Box 1538, Hobart,
Tas. 7001, Australia.
[C] Nuclear Physics Division, AERE Harwell, Oxon., OX11 0RA, England.

*Abstract*

Studies have been made of the approach to energy-loss and charge-state equilibrium of initially pure charge states of ions, transmitted through thin carbon targets. Ions of Li, F and Cl at 3 MeV per AMU were used. Detailed observations were made of outgoing energy losses and charge-state distributions, for outgoing charges equal to those ingoing. A Monte Carlo analysis is made of the charge changing processes, which allows calculation of energy losses due to projectile charge exchange. The residual electronic target-ionisation loss is analysed to predict in-target charge states of the projectile ions. Using these, a comparison is made between the in-target effective charge for target ionisation, and the averaged ionic charge which fits charge-exchange data.

## 1. Introduction

Charge exchange and energy loss comprise the major physical processes of interest in the interaction of swift ions in solids. Several comprehensive reviews exist on both topics: Betz (1972, 1980) on charge exchange; Andersen *et al.* (1977), Andersen (1983), as well as the detailed compilations of Ziegler and Chu (1974) and Ziegler (1980), on energy losses. It is evident, for example from data used in the last-named reference, that there are many gaps in the data in the region 1–10 MeV per AMU (MeV/U), while the theoretical interpretation is uncertain in several respects.

The present work describes a study of the approach to an equilibrium of both charge-state distribution and energy loss as an ion beam passes through an increasing thickness of target. Here, studies are reported of 3 MeV/U ions of Li, F and Cl in carbon targets. This continues work initiated by the Harwell group (Cowern *et al.* 1984) in a region of energy and mass where deviations from 'bare-nucleus' effects may be studied. The present work includes a description of the experiments, and an interpretation of the data to deduce the effective in-target charge states of the ions required to explain the measured energy losses. Such energy losses are only uniquely defined, for ions which may exist in multiple charge states, when the ingoing and

* Part III, *Aust. J. Phys.*, 1987, 40, 125.

0004-9506/88/050681$03.00

outgoing charge state are determined uniquely. This is so because the processes of energy loss are mediated by capture, loss and excitation of electrons, which depend on the ions' histories.

It is appropriate to describe the model by which realistic calculations may be made of the charge-exchange processes involved in a target. In principle, one should treat each ionic state as a many-body system, defined by a self-consistent wavefunction. This is not feasible where hundreds of particle shell combinations may exist, and it is usual to adopt the Slater (1930) picture in which electrons are described by independent-particle subshell quantum numbers ($n$, $l$), and the effective charge of the ion deduced from empirical screening factors. Then the cross sections for the various charge-changing processes may be calculated, using some well-known approximations: chiefly the first Born approximation for electron loss and excitation (Walske 1956; Merzbacher and Lewis 1958) and the OBK theory for electron capture (Betz 1980).

Given some experimental data on ion energy losses, one may attempt to fit these with standard theory. But the main source of disagreement is likely to be in the deficiency of the independent-particle model for the effective in-target charge of the ion, on which energy-loss processes depend sensitively. Therefore, for the present work we decided to use the data to predict the effective charge required by the Bethe–Bloch theory and compare this with the RMS averaged ionic charges from fits to data on the charge-changing processes in the target. In order to correspond to the effective change in energy loss the latter may be assumed to correspond to the effective charges as 'seen' outside the bound electron shells, so that the comparison should not depend on Slater self-screening factors.

Section 2 describes the experimental methods used for measuring outgoing charge fractions and projectile energy losses. In Section 3 we show a method of analysis by which the observed data may be displayed to represent the mean values, in-target, of the effective projectile charges. Such a method requires an allowance for contributions to energy loss by projectile ionisation, not included in the main 'Bethe–Bloch' target-ionisation process.

## 2. Experimental Method and Results

The 14UD accelerator provides a wide variety of ions with energy-to-mass ratios between 1 and 5 MeV/U. Beams are extracted with charge states resulting from terminal-stripper ionisation. Fig. 1 shows schematically how charge-changing processes are detected in the present work. After acceleration, a beam at 3 MeV/U—at 21, 57 and 105 MeV for $^{7}$Li, $^{19}$F and $^{35}$Cl respectively—is analysed through 90° (A), passed through a post-acceleration stripping foil (B) and allowed to enter a switching magnet (C) whose function is to switch to the beam line one of the range of charge states produced by the foil, and focus it to the target (D) in the spectrometer scattering chamber. A number (about 4 depending on energy) of the exit charge states are simultaneously focussed by the Enge magnet and recorded at points of the focal plane (E) which is instrumented for direct positional counting. Thus charge spectra may be measured, and with the resolution available, lineshape widths are about 1000 times less than charge-to-charge spacings. A complete charge spectrum may be obtained by using typically three settings of the spectrometer magnet.

The excellent resolution of the Enge spectrograph enables in principle a measurement of the shift of position of a peak after traversal of a target, and this was the basis

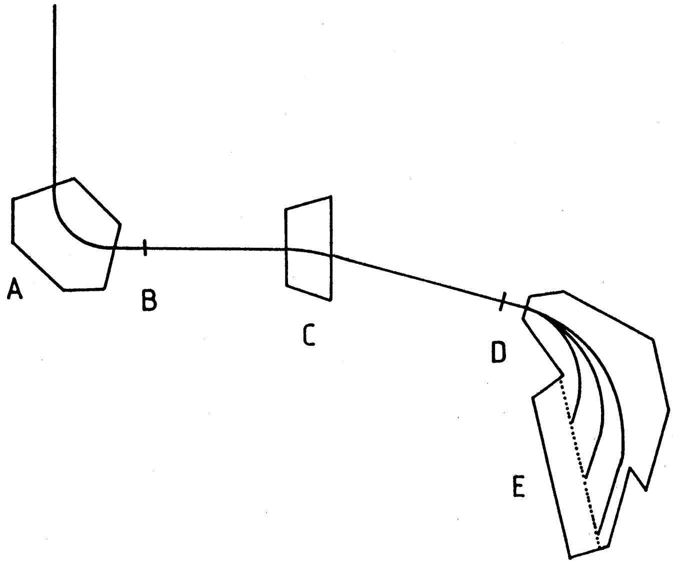


**Fig. 1.** Schematic layout of the experiment using separated charge states: A, 90° analysing magnet; B, post-acceleration stripper; C, charge-separator magnet; D, target; and E, Enge focal-plane detector.

of the method used for measuring energy losses. Energy losses in thin targets lay between 1–100 keV for 21–130 MeV ions, and for adequate accuracy it was found necessary to measure energy losses for all target thicknesses, simultaneously. The targets (up to eight with two blank positions) were mounted on a rotating carrier, and target positions were correlated in time using a shaft encoder, with a rotation frequency of 2 revolutions per second. The smallest measured shifts in the focal plane were near 0·1 mm, with a position resolution of order 1 mm. Small centroid shifts were, however, readily obtained in the manner described by Pender and Hay (1984). Such centroid shifts were always related to 'no-target' positions, and this required than the method could only be applied to ions whose ingoing and outgoing charge states were the same.

The measurements were carried out, for each ion beam and incident charge state, at four different but contiguous regions of the focal plane, using different Enge-magnet currents. This enabled an accurate calibration of the focal plane for small energy shifts, using a polynomial function. In addition, it allowed for any microscopic non-linearities in the focal plane, whose essential detecting element is a fine wire (Ophel and Johnston 1978). Thus for each charge state a set of four runs, with eight targets and two blanks, was obtained. The results of the measurements are displayed in Fig. 2. Energy losses deduced from focal-plane shifts, divided by effective target thicknesses, are plotted against target thickness. In the ordinates of Fig. 2, an extra thickness of $0 \cdot 3\ \mu g\,cm^{-2}$ was added to each target, equivalent in stopping power to $0 \cdot 15\ \mu g\,cm^{-2}$ oxygen and $0 \cdot 05\ \mu g\,cm^{-2}$ hydrogen. These values are discussed in Section 3*d* below. The errors plotted are from the scatter of points, with no attempt to include the effects of systematic variations, which will be discussed further in Section 4.

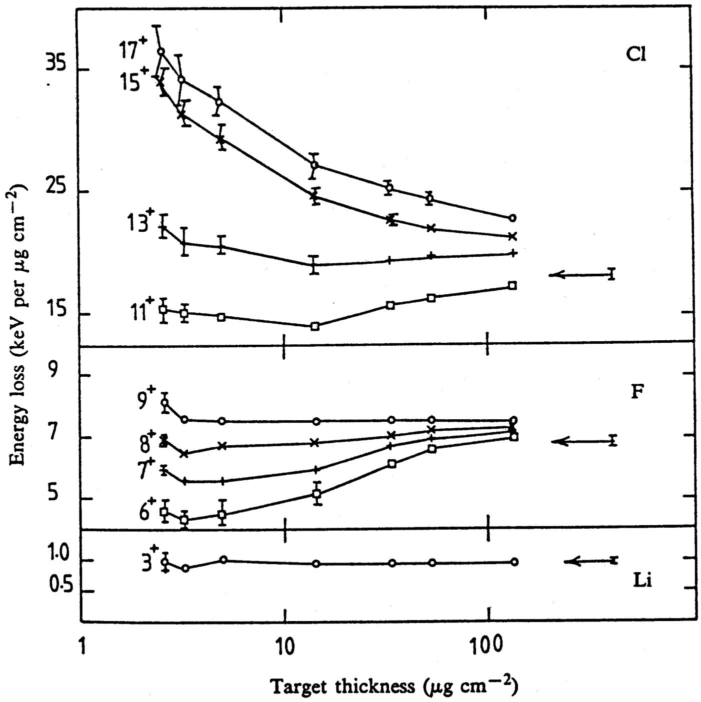


**Fig. 2.** Energy loss per carbon target thickness for ions entering targets at chosen ingoing and (the same) outgoing charge states (labelled) for Cl, F and Li ions at 3 MeV/U. Errors are from the experimental scatter of data. The arrows at the right represent the predicted thick-target, equilibrium, energy-loss values of Ziegler (1980).

Before embarking on an interpretation of the data, it is appropriate to note the composition of the targets used. These (and probably all such) targets contained the detectable impurities $O_2$ and $H_2$ mentioned above. All target-thickness measurements were made by detecting back-scattered 2 MeV protons; such measurements were very accurate, with $\leqslant 1\%$ error relative to one another, but are subject to a 5–10% error in the absolute back-scattering cross section (Jackson *et al.* 1953). Here there was, of course, a possible source of a systematic error and this was addressed as described in the discussion of Section 4.

## 3. In-target Projectile Charge States

The data of Fig. 2 may be modelled using energy-loss theory, which takes account of the interaction of an ion with electrons in the target ('electronic' loss), with nuclei in the target ('nuclear' loss), and exchange, that is, capture and loss of electrons by the projectile ('exchange' loss). As emphasised in Section 1, an assumption necessary for any practical calculation is that the projectile's charge state $Z_{\rm eff}$ is the nuclear charge screened by independently-orbiting electrons. Since the main (electronic) energy loss depends on this charge *squared*, the data provide a sensitive measure of that $Z_{\rm eff}$ which fits them. To obtain this, it is obviously necessary to calculate and allow for all effects other than electronic loss. As shown by Ziegler (1980, Vol. 5), for the 3 MeV/U projectiles discussed here, the nuclear loss is less than $10^{-3}$ of the rest, and it will not be considered further. In Sections 3*a*–3*c* below we describe the necessary fitting procedures: the basic physical processes in (*a*), the exchange loss in (*b*) and the numerical calculations in (*c*). The effective projectile charge states are deduced in Section 3*d*.

### (a) Physical Description of Energy-loss Processes

Chief and best-known among energy-loss processes is the target electronic loss as designated above. Summaries of the considerable literature on this subject have been given by Andersen (1983) and Ziegler (1980). Because there are different versions in the literature of the full dependence, we shall spell out the one we consider best justified:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi e^4 N}{m v^2} Z_{\mathrm{eff}}^2 L(v, Z_{\mathrm{eff}}, Z_{\mathrm{t}}), \tag{1}$$

where

$$L(v, Z_{\mathrm{eff}}, Z_{\mathrm{t}}) = L_0 + L_1 Z_{\mathrm{eff}} + L_2 Z_{\mathrm{eff}}^2 - c/Z_{\mathrm{t}}. \tag{2}$$

Here $e$ and $m$ are the electron charge and mass, $v$ the relative particle–target velocity, and $N$ and $Z_{\mathrm{t}}$ the target electron number density and (nuclear) charge. The terms in equation (2) are the so-called Bethe loss, and the Barkas, Bloch and shell corrections respectively:

$$L_0 = \ln(2mv^2/I) - \ln(1-\beta^2) - \beta^2, \tag{3a}$$

where the relativistic terms involving $\beta^2$ are of order $10^{-5}$ and will be neglected henceforth, and $I$ is a mean target ionisation potential. For the $L_1$ and $L_2$ corrections we define a parameter

$$\eta = Z_{\mathrm{eff}}(v_0/v),$$

using $v_0 = e^2/\hbar$ the first Bohr velocity: then the value derived by Lindhard (1976) for the Barkas correction is

$$L_1 Z_{\mathrm{eff}} = \frac{3\pi Z_{\mathrm{eff}} e^2 I}{2mv^3\hbar} L_0 = \frac{3\pi\eta}{2mv^2/I} L_0. \tag{3b}$$

Physically, the Barkas correction, as derived by Lindhard, takes account of the polarisability of the target atom in the presence of the projectile, and is assumed to be present for both 'close' and 'distant' collisions. This form does appear to agree with data (Andersen *et al.* 1977), though the theory of Sung and Ritchie (1983) would suggest that only distant collisions contribute and that the Lindhard correction is a factor of about 2 too large. We shall use equation (3b) here, in agreement with Andersen (1983).

The Bloch (1933) correction involves the complex psi-function

$$-L_2 Z_{\mathrm{eff}}^2 = -\psi(1) + \mathrm{Re}\{\psi(1+\mathrm{i}\eta)\},$$

which may be transformed (Erdélyi 1953) to

$$-L^2 Z_{\text{eff}}^2 = \sum_{n=1}^{\infty} \frac{\eta^2}{n(n^2+\eta^2)}. \tag{3c}$$

For $\eta > 1{\cdot}4$, one may use the asymptotic form

$$-L_2 Z_{\text{eff}}^2 = \gamma + \ln(\eta) + (12\eta)^{-2} + (120\eta)^{-4} + (252\eta)^{-6}, \tag{3d}$$

where $\gamma = 0{\cdot}577216\ldots$ is the Euler–Mascheroni constant. The result (3d) is within a few parts in $10^4$ of (3c). For $\eta \ll 1$, the limiting value of (3c) is $1{\cdot}202\eta^2$, which leads to the Bethe relation for energy loss, while for $\eta \gg 1$, (3d) goes to $\gamma + \ln(\eta)$ which, combined with the Bethe term, leads to Bohr's (1948) expression.

The shell correction ($-c/Z_t$ in equation 2) allows for the effect of binding of electrons in the target atoms. Its exact size is not significant here, since we shall relate the stopping of ions of F and Cl to that of Li in the *same* carbon targets. Such data as exist for carbon (cf. Ziegler 1980, Vol. 5) indicate that the shell correction is close to zero, within errors, for 3 MeV/U ions.

### *(b) Energy Loss in Charge-changing Cycles*

As proposed in Section 1, we now calculate the charge-exchange loss which is to be subtracted from the observed data of Fig. 3, in order to obtain $Z_{\text{eff}}$ using the equations of Section 3*a*. For the present purposes we are interested in the energy loss sustained by a projectile which enters, and emerges from, the target in the same charge state. This may evidently be approximated as the number of charge-changing cycles multiplied by the mean energy loss per cycle. More correctly, one should allow for the changing history of the in-target ionic charge.

To obtain the energy loss in a charge-exchange cycle, it is first necessary to discuss the kinematics of the collision processes. (We are not aware of any such discussion, delineating the accuracy of calculations, in the literature.) Consider a projectile (mass $P$) and a target atom (mass $T$) exchanging an electron (mass $m$). This is a 3-body problem, usually reduced (e.g. Bohr 1948) to a 2-body problem by invoking the relative smallness of the electron-to-ion mass ratio. For the majority of ionising collisions in which nuclear energy loss is ignorable, the projectile is virtually undeflected. For such cases the energy loss due to electron exchange may be described as a distant or 'soft' collision, in which momentum conservation only in the direction of the incident beam need be imposed.

Solution of the equations of energy and momentum conservation for the *capture* process (masses $P$, $T$, $m$)

$$P + (T+m) \rightarrow (P+m) + T$$

leads to the expression for the projectile energy loss

$$\Delta E_{\text{cap}} = B_T - B_P + E_P \frac{P}{4T}\left(\frac{P+m}{P}\,\frac{B_T - B_P}{E_P} - \frac{m}{P}\right)^2, \tag{4}$$

where $B_T$ and $B_P$ are the (positive) binding energy of the electron to the target and projectile cores, for an incident projectile energy $E_P$. Equation (4) is accurate to second order in both $m/P$ and $(B_T - B_P)/E_P$, both of these terms being typically of order $10^{-4}$. Hence the energy loss on capture requires no significant correction to the binding energy-difference.

For the *loss* process

$$(P+m)+T \rightarrow P+m+T,$$

the soft-collision restriction enables us to solve the 3-body problem by noting that the emerging electrons' average distribution in the reference frame of $P$ is predominantly isotropic (Drepper and Briggs 1976). Its average velocity relative to $P$ thereby becomes very small, and the momentum–energy balance equations yield

$$\Delta E_{\text{loss}} = \tfrac{1}{2}mv^2 + \frac{P}{P+m}B + E_P\frac{P}{4T}\left(\frac{B}{E_P}\right)^2, \tag{5}$$

where $v$ is the laboratory-frame velocity of $P$, $B = B_P + E_C$, and $E_C$ is the mean kinetic energy of separation of $P$ and $m$.

To the same order of accuracy as used in equation (4), the energy loss in a charge-changing cycle becomes

$$\Delta E = B_T + \tfrac{1}{2}mv^2 + E_C. \tag{6}$$

The first two terms represent the sum of the energy necessary to ionise a target electron, and the kinetic energy of an electron accelerated to the projectile's velocity. The term $E_C$ follows from a study of the dynamics of the Born calculation (Walske 1956). It is the continuum energy loss, which expresses the fact that, relative to the projectile, the ionised electron carries away a positive mean kinetic energy $E_C$. In the work of Cowern *et al.* (1984) this was assumed to be a fitted parameter. For the present work it was taken as the ratio of the 'energy-loss' and 'loss' cross sections, calculated in first Born approximation. The value computed by us for 36 MeV C ions is 0·29 keV, close to the value 0·30 keV adopted by Cowern *et al.*

### *(c) Calculation of Projectile Energy Loss*

In order to obtain finally the projectile's energy loss due to target ionisation, it is necessary to know how much energy is lost in the charge-changing cycles, in each cycle of which the energy $\Delta E$ of equation (6) is lost. This depends on the mechanisms of charge changing in the target. Emergent mean charge states for Cl and F are plotted in Fig. 3 as functions of the target thickness, for various incident charge states. The approach towards equilibrium with thick targets ($\geqslant 50\ \mu g\,cm^{-2}$) is evident. The results for Li are not displayed, as for all targets there was virtually full stripping to mean outgoing charge state $3^+$.

In order to follow the charge-changing cycles, it was necessary to fit the emergent charge-state distributions with the basic cross sections for capture, loss and excitation of the projectile. In earlier work (Hay *et al.* 1984) we have described a Monte Carlo method of doing this. The same procedure was followed for the data of Fig. 3, leading to the fitted curves shown there. The fits required scale factors on the theoretical OBK capture cross sections of 0·81 and 0·77 for Cl and F, and 0·85 for loss with both ions. Using the averaged 'history' of charge changing, it was possible, using equation (6), to deduce the projectile's charge-changing loss and, at the same time, the Bethe, Barkas and Bloch losses for the corresponding $Z_{\text{eff}}$ defined, as was explained

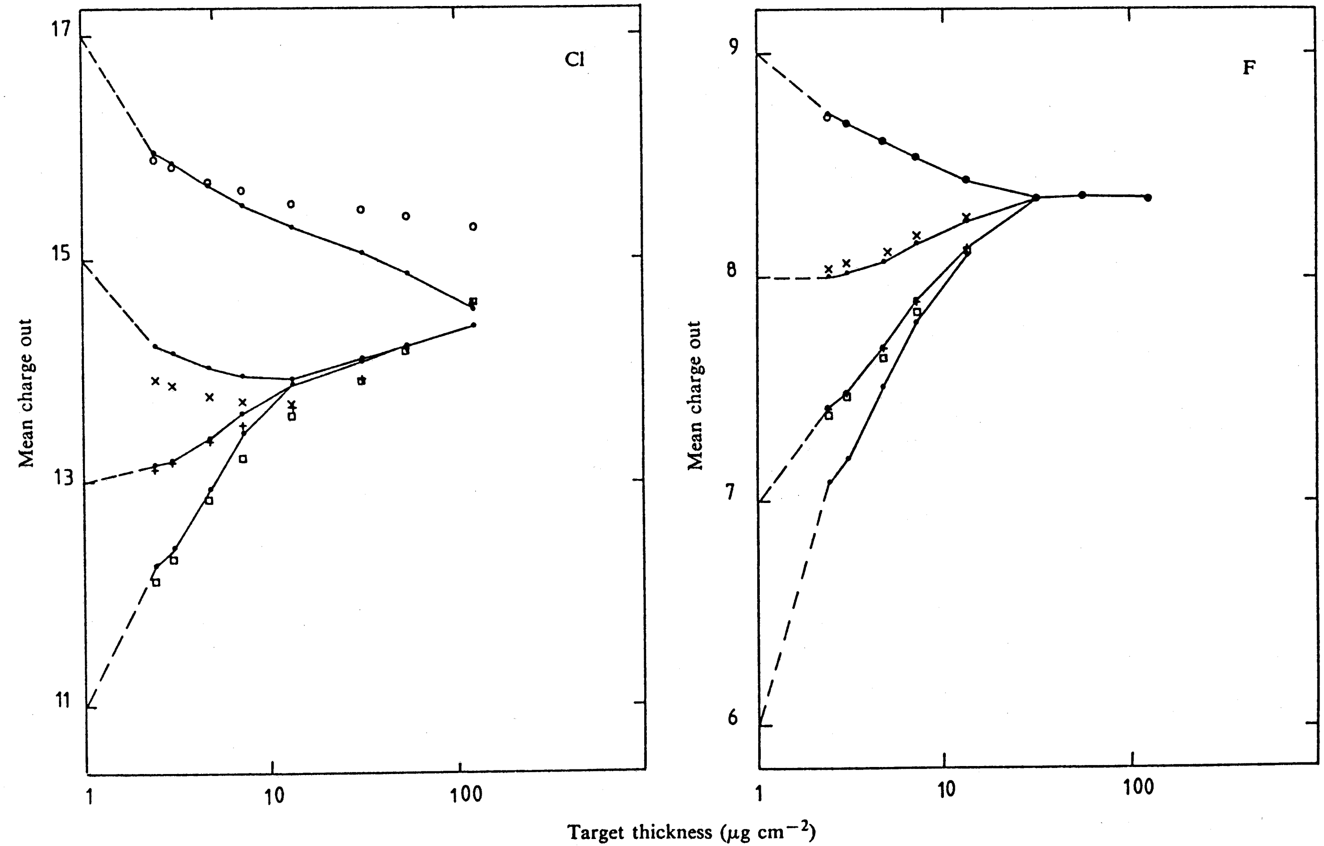


**Fig. 3.** Mean charge of emergent ions as functions of carbon target thickness, for incident 3 MeV/U Cl and F ions. The incident charge states are the intercepts of the dashed curves at the ordinate. The data are plotted as full circles, and joined by the solid lines, while calculated values are represented by the open symbols.

in Section 1, to be fully screened by all attached bound electrons. Losses due to X-ray and Auger emissions were also included in the calculations. Apart from the (near-unity) scale factors for cross sections, no arbitrary parameters were required for the separate calculation of the several contributions to energy losses.

### (d) Effective Projectile Charge States

Equation (1) is the basis from which it is possible to derive $Z_{\mathrm{eff}}$ from observations, but it is first necessary to allow for small losses due to the oxygen and hydrogen impurities in the carbon targets, and for the loss due to charge-changing effects in the projectile. The impurities were treated by equating them to an equivalent thickness of carbon. Examination of the empirical fitting to stopping powers done by Ziegler showed that for 3 MeV/U ions of Li, F and Cl, the stopping power for oxygen is 0·9 and for hydrogen 2·6, relative to carbon. Hence the measured average oxygen and hydrogen thicknesses of 0·15±0·03 and 0·05±0·02 $\mu g\,cm^{-2}$ have been replaced by 0·3 $\mu g\,cm^{-2}$ of carbon (this was already included for the ordinate of Fig. 2). This amounts to some 10% extra thickness for the thinnest target at 2·58 $\mu g\,cm^{-2}$.

The projectile loss due to charge exchange is not of importance in studies of energy losses of ions which remain fully stripped in targets. With the present data at 3 MeV/U this is closely true for Li, for which the exchange loss amounts to only 1% of the total. For F and Cl it can be up to 10%.

**Table 1. Selected data and fits as plotted in Figs 2–4 for chosen ion charge states and target thicknesses**

Derivation and comparison of $Z_{\mathrm{eff}}$ and $Z_{\mathrm{RMS}}$ are in the text. Target thicknesses (in $\mu g\,cm^{-2}$) are:

| | Nominal | Corrected |
|---|---|---|
| a | 2·58 | 2·73 |
| b | 14·3 | 13·74 |
| c | 133·3 | 125·6 |

| Ion (charge) | Target thickness | Energy loss | Exchnge loss | $Z_{\mathrm{eff}}$ | $Z_{\mathrm{RMS}}$ |
|---|---|---|---|---|---|
| Cl(17+) | a | 37·2±2·2 | 1·25±0·25 | 19·1±0·6 | 16·6 |
| | b | 27·6±1·1 | 2·30±0·35 | 16·0±0·3 | 15·5 |
| | c | 23·2±0·1 | 2·25±0·16 | 14·4±0·1 | 14·6 |
| Cl(11+) | a | 15·7±1·0 | 1·38±0·12 | 11·9±0·4 | 11·0 |
| | b | 14·2±0·2 | 1·81±0·18 | 11·1±0·1 | 12·1 |
| | c | 17·6±0·1 | 1·81±0·10 | 12·5±0·1 | 13·2 |
| F(9+) | a | 8·29±0·29 | 0·33±0·01 | 8·8±0·2 | 8·92 |
| | b | 7·70±0·13 | 0·47±0·02 | 8·4±0·1 | 8·76 |
| | c | 7·71±0·01 | 0·49±0·02 | 8·4±0·1 | 8·45 |
| F(6+) | a | 4·73±0·32 | 0·74±0·02 | 6·2±0·3 | 6·49 |
| | b | 5·29±0·38 | 0·49±0·02 | 6·8±0·3 | 7·16 |
| | c | 7·14±0·05 | 0·52±0·02 | 8·0±0·1 | 8·28 |
| Li(3+) | a | 1·01±0·13 | 0·010±0·001 | 3·06±0·20 | 2·998±0·0005 |
| | b | 0·97±0·02 | 0·011±0·002 | 3·01±0·03 | 2·998±0·0005 |
| | c | 0·967±0·002 | 0·011±0·001 | 2·99±0·01 | 2·998±0·0005 |

The results of the analysis are shown in Table 1, for some representative target thicknesses, for the highest and the lowest charge states in Cl and F. The observed energy loss is listed in the third column, and the predicted mean component due to projectile charge exchange in the fourth column. The target loss (column 3

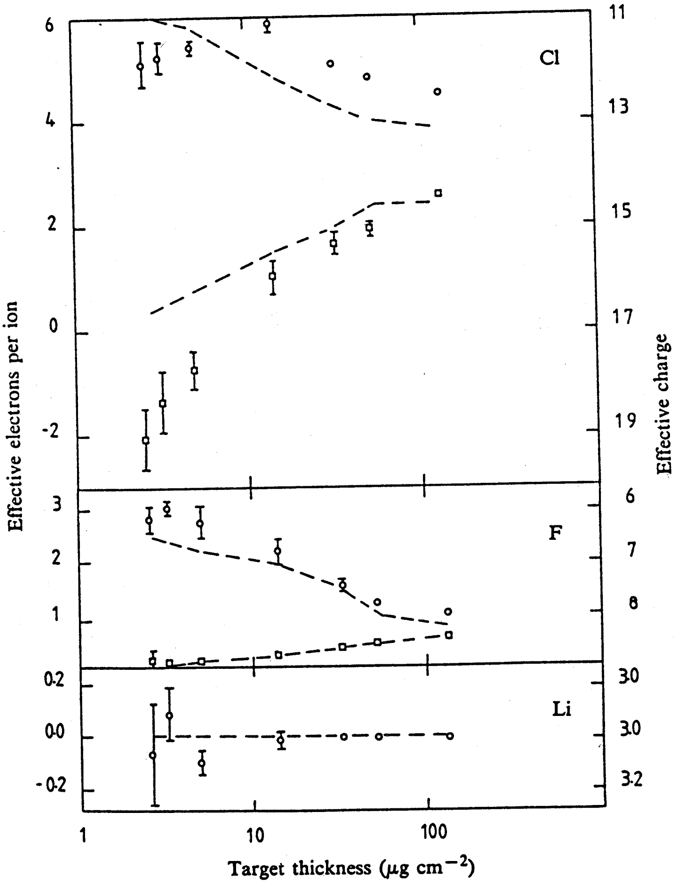


**Fig. 4.** Comparison of in-target averaged ion charge obtained from energy-loss and charge-exchange data. The dashed curves represent RMS ionic charge states corresponding to the fits of Fig. 3; the plotted points are deduced from the energy-loss data, for charge states as described in the text.

minus column 4) corresponds, with the Bethe–Bloch theory, to the $Z_{\text{eff}}$ values of column 5, which is compared with the averaged (RMS) charge $Z_{\text{RMS}}$ fitted in-target charge state of column 6. It should be pointed out that the $dE/dx$ figures given in the third column have been corrected for a deduced systematic error; this will be discussed in Section 4.

The results of such calculations for all targets are plotted in Fig. 4, which shows (dashed curves) the averaged in-target ionic charges and (points) the deduced $Z_{\text{eff}}$ values. Generally, the two sets follow similar trends, but we note that the fitted $Z_{\text{eff}}$ values actually exceed the bare-ion values, for the $17^+$ charge state of Cl, with thin targets. This discrepancy will be discussed in the following section.

## 4. Discussion of Results

Before considering the results embodied in Fig. 4 and Table 1, we discuss possible systematic effects in our experiments, that could lead to a misinterpretation of our results.

As pointed out in Section 2, the observed $\mathrm{d}E/\mathrm{d}x$ values of Fig. 2 contain only random errors. However, they depend on accurate knowledge of target thicknesses. These were obtained from published absolute back-scattering cross sections for proton–carbon scattering (Jackson *et al.* 1953), with errors stated to be at least 5%. One way to improve on their accuracy, which we have adopted, was to compare the experimental and predicted thick-target $\mathrm{d}E/\mathrm{d}x$ values for Li. The latter, based on the well-known Bethe–Bloch theory for fully stripped ions, should be very accurate, while the statistical errors in the former are of order only 0·2%. In fact a discrepancy greater than this was found: the target thicknesses we measured needed to be adjusted downwards by 6% in order to make the two agree. Such an adjustment implied that the quoted $^{12}\mathrm{C}+\mathrm{p}$ back-scattering cross section is 6% too low; allowing for an extra error in our experiment due to extrapolating in angle, this is acceptable.

If we refer to the results of Fig. 4, since our measurements are accurate within the statistical accuracy shown, it seems clear that the increase of $Z_{\mathrm{eff}}$ for these targets and high charge states must be real and caused by the presence of some energy-loss process at the entrance (or exit) surface not accounted for by the Bethe–Bloch and projectile-loss processes. This trend is also clearly seen in the results of Fig. 2, in which virtually all $\mathrm{d}E/\mathrm{d}x$ curves tend upwards at the thinnest targets (note that this is not due to impurities whose thicknesses were included in effective target thicknesses). Mechanisms such as 'sparking due to image-charge formation', 'energy expended in forming a wake', might be considered as possible speculative causes of this effect. We have not investigated such possibilities.

In the trend of the $\mathrm{d}E/\mathrm{d}x$ values towards equilibrium (illustrated by the Ziegler values plotted with arrows in Fig. 2) another significant anomaly shows in the Cl data, namely the relative closeness of the values for charge states 15 and 17. We believe that this may be due to an enhanced energy loss in the $15^+$ (helium-like) ion due to components of the incident beam containing a metastable two-electron state which has been excited by the post-stripper foil (cf. Fig. 1) some 10 m upstream of the target. Evidence for such helium-like states has been observed elsewhere in atomic-physics studies (Fano 1983), but it is not clear how one should allow quantitatively for this effect.

We conclude that the experimental data we have observed on energy losses of ions in solid targets, not surprisingly, conform to Bethe–Bloch theory and the standard cross sections used to calculate charge-exchange phenomena in (solid or gas) targets. Our method of comparing these, namely the similarity of effective in-target charge states as fitted to $\mathrm{d}E/\mathrm{d}x$ and as calculated from fits to charge fractions, does show up an apparent extra energy loss at the target surface, not accounted for by the usually-discussed mechanisms.

Since the extra energy-loss process appears to be a surface-related effect, it would obviously be enhanced by a study of the same phenomenon using targets thinner than the thinnest ones we were able to use without breaking ($\sim 2\cdot 5\ \mu\mathrm{g\,cm}^{-2}$). A comparison of thin solid and gas targets would also be of great interest.

## References

Andersen, H. H. (1983). *Phys. Scripta* **28**, 268.
Andersen, H. H., Bak, J. F., Knudsen, H., and Nielsen, B. R. (1977). *Phys. Rev.* A **16**, 1929.
Betz, H.-D. (1972). *Rev. Mod. Phys.* **44**, 465.

Betz, H.-D. (1980). *In* 'Atomic Physics—Accelerators' (Ed. P. Richard), Ch. 3 (Academic: New York).
Bloch, F. (1933). *Ann. Phys. (Leipzig)* **16**, 285.
Bohr, N. (1948). *Mat. Fys. Medd. Dan. Vid. Selsk.* **18**, no. 8.
Cowern, N., Read, P. M., Sofield, C. J., Bridwell, L. B., Huxtable, G., and Miller, M. (1984). *Phys. Rev.* **30**, 1682.
Drepper, F., and Briggs, J. S. (1976). *J. Phys.* B **9**, 2063.
Erdélyi, A. (Ed.) (1953). 'Higher Transcendental Functions', Vol. 1 (McGraw–Hill: New York).
Fano, U. (1983). *Rep. Prog. Phys.* **46**, 97.
Hay, H. J., Pender, L. F., and Treacy, P. B. (1984). *Nucl. Instrum. Methods* B **2**, 505.
Jackson, H. L., Galonsky, A. I., Eppling, F. J., Hill, R. W., Goldberg, E., and Camerson, J. R. (1953). *Phys. Rev.* **89**, 365.
Jackson, J. D. (1975). 'Classical Electrodynamics' (Wiley: New York).
Lindhard, J. (1976). *Nucl. Instrum. Methods* **132**, 1.
Merzbacher, E., and Lewis, H. W. (1958). 'Handbuch der Physik', Vol. 34 (Springer: Berlin).
Ophel, T. R., and Johnston, A. S. (1978). *Nucl. Instrum. Methods* **157**, 461.
Pender, L. F., and Hay, H. J. (1984). *Nucl. Instrum. Methods* B **4**, 72.
Slater, J. C. (1930). *Phys. Rev.* **36**, 57.
Sung, O., and Ritchie, R. H. (1983). *Phys. Rev.* A **28**, 674.
Walske, M. C. (1956). *Phys. Rev.* **101**, 940.
Ziegler, J. (1980). 'Handbook of Stopping Cross Sections', Vols 1–5 (Pergamon: New York).
Ziegler, J., and Chu, W. K. (1974). *At. Data Nucl. Data* **13**, 463.

Manuscript received 13 April, accepted 19 May 1988