Charge-exchange effects in the energy-loss straggling of ^{16}O ions in Al

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The energy-loss straggling of ^{16}O ions incident at energies from 5 to 50 MeV on Al foils of thickness 100 to 500 μg/cm^2 has been measured. Although the collisional straggling at energies above 25 MeV is expected to be appropriately described by the Bethe-Livingston theory of straggling, the data give values about a factor of 2 greater than this theory. The uniformity of the foils was studied and the limits to systematic errors that arise from this source were found to be small. The difference between the Bethe-Livingston theory and experiment is interpreted in terms of charge-exchange fluctuations. Monte-Carlo calculations have been made for ^{16}O ions at 40 MeV (where only two charge states predominate), and the charge-exchange cross sections (8×10^{-18} cm^2/atom for $\sigma_{7^+ \to 8^+}$ and $\sigma_{8^+ \to 7^+}$) required to produce a fit to the data are found to be similar in magnitude to those measured by Macdonald and Martin for 40-MeV ^{16}O incident on N_2 and Ar gas targets.

I. INTRODUCTION

The average energy loss and the charge-state distribution of partially stripped ions following their passage through matter have received considerable attention, and the connection between the energy loss and the mean effective charge in the target has been studied.[1-4] Such work has led to useful semiempirical expressions for predicting the energy lost by the ions through excitation and ionization of atoms in the target.[5,6]

The study and interpretation of fluctuations in the energy loss about its mean value, i.e., the energy-loss straggling, have in the case of partially stripped ions received much less attention, although some experimental data have recently become available.[7-11]

The straggling resulting from fluctuations in collisional excitation and ionization of the target atoms is predicted for ions with a *constant* charge by several formulations of straggling theory.[1,12-14] The Bethe-Livingston theory,[14] for example, is applicable for ion velocities corresponding to the higher range of ^{16}O ion energies used in the experiments to be described here. The Bethe-Livingston formula is usually adapted to the case of partially stripped ions, which do not have a constant charge, by inserting for the ion charge the value of the "effective charge" obtained from energy-loss measurements. However, this procedure does not take account of the effect of fluctuations of the average charge of individual ions about the root-mean-square value. Thus a broadening of the energy distribution, related to the charge-exchange processes, might be expected in addition to that due to the fluctuations in the collisional energy losses. Vollmer[15] has shown that the charge-exchange contribution to straggling can be calculated in terms of charge-exchange cross sections, using a Monte Carlo method. More recently Winterbon[16] has presented a semianalytic method for the calculation of straggling which takes account of charge exchange. Vollmer's calculations, and also those of Efken *et al.*,[8] for straggling in gas targets for which measurements of charge-exchange cross sections are available, indicate that the contribution to the overall straggling arising from charge-state fluctuations may be as much as or more than that theoretically predicted for collisional straggling. In the case of partially stripped 400 keV to 2 MeV α particles traversing a Kr gas target Besenbacher *et al.*[11] concluded that published charge-exchange cross sections for He in Kr gave a reasonable account of their observation of excess straggling over that predicted by the Bohr theory, which takes account only of collisional excitation and ionization of the target.

The experimental observations made with gas targets by Efken *et al.* also demonstrated straggling widths large compared with collisional theory predictions, in qualitative accord with their calculation for similar ions and targets. A direct quantitative comparison of experiment with theory was precluded by the lack of the charge-exchange cross section values appropriate to the experimental cases.

Considering now the case of solid targets, Avdeichikov *et al.*,[7] and Schmidt *et al.*[10] found values of energy straggling of heavy ions in solids much greater than those expected solely from the theoretical predictions of collisional excitation of the target. By analogy with the gas-target data it appears that, with solid targets also, charge-exchange processes make a large contribution to straggling of partially stripped ions. However, none of the charge-exchange cross sections required to carry out detailed estimates of the effects of charge-state fluctuations are available in these cases. The dependence of energy-loss straggling of heavy ions on charge-exchange is of considerable interest as it may provide a means of gaining information about this process. Furthermore a demand for data on straggling has arisen due to the general increase in interest in heavy ion physics. For example heavy-ion straggling is of practical interest in the stripping of heavy ions in particle accelerators,[17,18] and in its effects on the resolution of $\Delta E - E$ telescopes.

We have therefore carried out measurements of the energy-loss straggling of partially stripped oxygen ions traversing thin Al foils of 100 to 500 $\mu g/cm^2$ thickness for incident energies in the range 5–50 MeV. At the lower end of this range oxygen ions have on average half of their orbital electrons attached, whereas at the upper end they have mainly only one, or two, K-shell electrons still attached.[27] The velocity of the oxygen ions for energies greater than about 20 MeV is such that the approximations normally made in the theory of energy straggling due to collisional excitation and ionization of the target are expected to be reasonable. The target material was chosen primarily to satisfy the practical requirement of obtaining a target of good thickness uniformity, as thickness fluctuations can readily contribute a dominant source of straggling.[19]

II. EXPERIMENTAL METHOD

A. Straggling measurements

The ^{16}O ions were accelerated using the Harwell tandem accelerator and were produced with energies in the range 5–48 MeV. In order to reduce the analyzed beam intensity, which was typically $\approx 1\ \mu A$, to a level suitable for detection with a surface-barrier detector, a thin Au-on-C foil (≈ 20-$\mu g/cm^2$ Au on 5-$\mu g/cm^2$ C) was used to scatter the primary beam. An ORTEC F series surface-barrier detector was mounted with its axis in line with particles scattered in the horizontal plane at 15° to the direct beam. A Ta collimator with two 1-mm-diam holes placed symmetrically above and below this axis was located in front of the detector in a plane normal to the scattered beam. One of the holes was left free while the other was covered with the Al foil to be examined. This arrangement is shown schematically in Fig. 1.

The signals from the detector were processed with amplification followed by pulse-height analysis. The linearity of the system was checked using a pulser. The pulser was also used to check that gain drifts were not significant.

This system thus allowed the accumulation of a spectrum containing two peaks: one due to ions

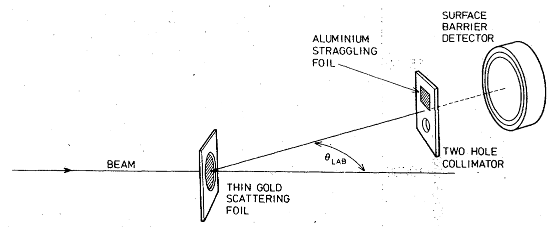

FIG. 1. Schematic arrangement of apparatus used for straggling measurements. The two-hole collimator system shown allows a measurement of the straggled and unstraggled beam at the same time.

not passing through the Al foil, referred to briefly as the "unstraggled" peak, and the other due to ions which did pass through the Al foil, the "straggled" peak. Both peaks contained the same contributions due to beam energy spread from the accelerator, straggling in the Au-on-C foil, kinematic energy spread, slit scattering and detector resolution, in short the system response function, while the straggled peak also contained the contribution from straggling in the Al target foil.

Using the above procedure, typical count rates at the detector were kept to about 100 counts/sec. The total dose was sufficiently low to prevent significant carbon build-up on the Al foils. The collection of the straggled energy distribution and the instrument function in the same run eliminated time-dependent changes such as the effects of radiation dose on detector resolution. A further advantage of this technique was the direct way in which the energy loss of the ^{16}O ions in the Al foils was obtained, the position of the unstraggled full energy peak being used for energy calibration. A typical spectrum obtained in this way is shown in Fig. 2.

B. Foils

Measurements of straggling are very prone to systematic errors arising from nonuniformities in the target. Several authors have noted difficulties with this aspect of straggling measurements[7,8,10] and indeed some discrepancies between theory and experiment for fully stripped α particles traversing Al foils have recently been shown to arise from such systematic errors.[7,19-21]

The Al foils used for our ^{16}O straggling measurements, of thicknesses 110, 246, and 457 $\mu g/cm^2$, were prepared by vacuum evaporation, as were Al foils used by us in studies of foil uniformity[19] and α-particle straggling.[20] The mean thickness of each Al foil was estimated from measurements of the energy loss of 20-MeV incident energy ^{16}O ions on their passage through the foil. The dE/dx value corresponding to the mean energy of the ion in the foil was obtained by linear inter-

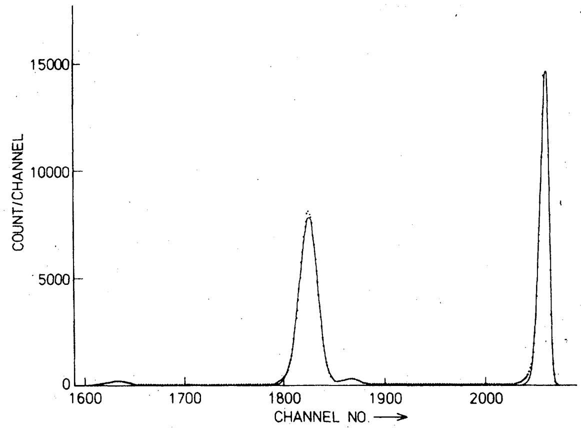

FIG. 2. Typical spectrum of the straggled (left) and unstraggled (right) ^{16}O beam. Two small peaks due to recoil carbon ions originating from the Au-C scatter foil can also be seen. The continuous line through the data points was obtained by nonlinear least-squares fitting of Gaussian line shapes.

polation of the dE/dx values measured by Booth and Grant[22] and the foil thickness was estimated from this value and our measured energy loss. From the uncertainties in the dE/dx values, the uncertainty in the foil thickness is estimated to be about 3%.

Investigations of the thickness uniformity of Al foils of ~160 $\mu g/cm^2$ (similar to the thinnest of those used in this work) using a 25-μm-diam proton beam[19] and a 2×0.1 μm Talystep profiler[20] have already been reported. Surface fluctuations of ±2.5 to 4.5 nm were observed, and the thickness fluctuations in these foils were estimated to be at most 2% to 3% (standard deviation σ), taking account of the finite resolution of the Talystep instrument and assuming similar, uncorrelated structure at both surfaces of the foil. The percentage thickness fluctuations in the thicker foils used in the present study should be less, since the absolute magnitude of the fluctuations about the mean thickness was expected to be no greater than for the thinnest foils, in accordance with the theory of the foil-formation process.[23] Additional Talystep measurements on a 500-$\mu g/cm^2$-Al foil on a glass slide in fact showed a mean surface fluctuation of about 5 nm, comparable with the values which had been found for a 160-$\mu g/cm^2$ foil. These measurements were made on an Al layer evaporated onto a clean glass slide without a release agent. For comparison, a Talystep measurement was also made on a 500-$\mu g/cm^2$-Al foil on a glass slide which had previously been coated sparsely with RBS25 release agent. In this case the thickness fluctuation was about 8 nm. This would correspond to at most 1% (σ) for the subsequently mounted self-supporting foil if it were assumed that all of the observed fluctuations were reflected in the Al and that the underside of the foil contributed independently the same degree of fluctuation as that measured on the upper surface. This estimate of the upper limit is thus a very conservative one.

Other sources of foil nonuniformity such as those arising from contamination by the material of the evaporation boat and alignment of the crystallites of the polycrystalline Al foils have been previously investigated[20] and found to be negligible.

III. RESULTS

An estimate of the energy straggling experienced by ^{16}O ions on their passage through the Al foil was obtained from each observed energy spectrum by effectively unfolding from the straggled peak the system response function represented by the unstraggled peak. The analysis was first carried out by nonlinear least-square fitting[24] of Gaussian line shapes to the spectra. These line shapes were found to give reasonable fits to both the unstraggled and the straggled peaks, apart from small mismatches in the low-energy tail and at the peak of each line shape, as can be seen in Fig. 2.

Recoil carbon ions from the Au-C scatter foil also appeared in the spectra as two peaks, one straggled and the other unstraggled. Nevertheless on the few occasions when one of these overlapped the ^{16}O straggled group, its intensity was too small to give a significant contribution to the width of the ^{16}O group.

The straggling was determined as the full width at half maximum (FWHM) of the straggled peak after the corresponding width of the unstraggled peak had been subtracted in quadrature, this procedure being equivalent to unfolding the contribution of the unstraggled peak if the line shapes were Gaussian. After the essentially Gaussian form of the line shapes had been satisfactorily established in several cases, the FWHM for each peak was subsequently extracted by the simpler procedure of fitting straight lines to the data points in the region of half-maximum height on each side of the peak, and estimating the width from the separation of these lines at half-maximum intensity. The experimental error in this estimate was inferred by noting the variation in full width corresponding to the uncertainty in the half height determined by counting statistics at the peak of the distribution.

The results obtained for the straggling of ^{16}O ions with incident energies in the range 5 to 50 MeV traversing Al foils of thickness from 100 to 500 $\mu g/cm^2$ are summarized in Table I and shown in Fig. 3. Statistical errors are given in the table. Possible systematic errors in the results are discussed below.

The limits to systematic errors in the straggling measurements due to foil nonuniformities were estimated using the limiting values of the percentage standard deviations of thickness fluctuations $(\sigma_{\Delta x}/\Delta x)$ discussed in Sec. II B. Assuming a constant dE/dx through the foil, and the measured energy loss ΔE in each straggling experiment, the corresponding standard deviation of the energy distribution due to thickness fluctuations was $\sigma_{\Delta E} = \Delta E(\sigma_{\Delta x}/\Delta x)$. The equivalent FWHM was subtracted in quadrature from the observed value of straggling to give an estimate of the limit to systematic effects on the straggling measurement due to foil nonuniformities. The conclusion arrived at was that systematic errors from this cause for ^{16}O ions of 40-MeV incident energy were unlikely to exceed 7% for the 110-$\mu g/cm^2$-Al foil $(\sigma_{\Delta x}/\Delta x \leq 2.5\%)$, 6% for the 246-$\mu g/cm^2$ foil $(\sigma_{\Delta x}/\Delta x \leq 1.75\%)$, and 4% for the 457-$\mu g/cm^2$ foil $(\sigma_{\Delta x}/\Delta x \leq 1\%)$. At 5-MeV incident energy the systematic errors might be as high as 20% for the 110-$\mu g/cm^2$ foil, 17% for the 246-$\mu g/cm^2$ foil, and 9% for the 457-$\mu g/cm^2$ foil. These figures were not treated as corrections to be applied to the results since they were regarded as upper limits rather than most-probable values. They thus represent the extent of possible uncertainties additional to the statistical errors shown in the presentation of the results.

The energies of the ^{16}O ions incident on the thin Au-on-C scatter foil were known from the accelerator analyzing magnet calibration, but had to be corrected for energy loss in the scatter foil, and for kinematic effects in scattering through 15°,

TABLE I. Energy loss and straggling for ^{16}O ions in Al foils.

Incident energy (MeV ± 1%)	Energy loss (MeV ± 1%)	Straggling FWHM (keV)
	110-μg/cm^2-Al foil	
39.70	0.528	90 ± 2
34.73	0.563	91 ± 2
29.75	0.598	93 ± 2
24.77	0.661	100 ± 2
19.79	0.699	103 ± 2
14.82	0.743	97 ± 2
9.85	0.756	91 ± 2
4.88	0.725	77 ± 2
	246-μg/cm^2-Al foil	
46.92	1.13	126 ± 4
43.68	1.17	133 ± 2
39.70	1.23	135 ± 2
34.73	1.30	145 ± 2
29.75	1.40	148 ± 3
19.79	1.59	161 ± 2
9.85	1.72	152 ± 2
4.88	1.65	126 ± 2
	457-μg/cm^2-Al foil	
44.68	2.17	182 ± 4
39.70	2.30	191 ± 4
34.16	2.46	199 ± 5
29.27	2.63	204 ± 7
24.77	2.82	219 ± 4
19.79	2.99	218 ± 3
14.82	3.19	220 ± 2
9.85	3.15	206 ± 2

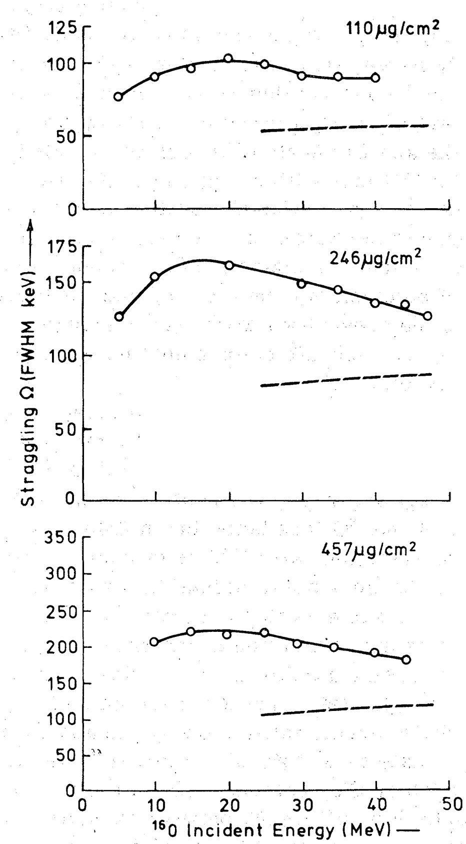

FIG. 3. Straggling measurements of ^{16}O ions traversing various thicknesses of Al foil. The continuous lines through the data are drawn by hand. The calculated straggling using the Bethe-Livingston theory is shown by broken lines.

to give the energies of the ^{16}O ions incident on the Al foils. The errors associated with these corrections arose from an uncertainty in the scatter foil thickness and in the precise scattering angle, but amounted at most to a systematic error of 60 keV, or 1.2% for the lowest energy ^{16}O used (5 MeV). Systematic errors in the spectrum energy calibration which arose due to uncertainties in the zero-energy intercept of the pulse-height analysis system were less than 1%, while additional errors in the energy loss and straggling due to departures from linearity were negligible.

IV. DISCUSSION

A. Comparison of results with straggling theory

We now turn to a comparison of the data with predictions from theories of collisional straggling; that is, the straggling resulting from fluctuations in collisional excitation and ionization of the Al target atoms by ^{16}O ions assumed to have a constant charge equal to the root-mean-square charge. The theories take several forms,[1,12-14] each closely related to a corresponding theory of electronic stopping power. They are valid in ion velocity ranges that differ according to the approximation used in their formulation.[2] We shall consider primarily the theory of straggling given by Bethe and Livingston,[14] which is expected to be valid for ^{16}O ions with energies greater than about 25 MeV.[2,25] The Bethe-Livingston theory is more appropriate here than the frequently used Tschalär theory[26] since it includes a more reasonable treatment of electron binding effects, and the targets used in the present work were thin enough not to require the Tschalär refinements necessary for thick targets.

The calculation of the collisional straggling using the Bethe-Livingston theory was carried out as described[20] for the computation of 5.5-MeV α-particle straggling in Al, the root-mean-square charge of the ^{16}O ions being taken from charge-state-distribution data.[27] This of course assumed that the charge-state distribution inside the Al target was the same as that observed externally, an acceptable approximation in the case of fast ^{16}O ions traversing a solid target. Evidence supporting this is the near equality of the rms charge outside the target, taken from Booth and Grant's charge-state data,[22] and the internal "effective" charge which they calculated from their energy-loss data; the difference between these two charges was less than 5% for ^{16}O ions in C and Au targets. The values of straggling calculated using the Bethe-Livingston theory are shown in Fig. 3.

It is obvious that the observed straggling of the partially-stripped ^{16}O ions is in all cases considerably greater than the Bethe-Livingston prediction. In fact at 40 MeV the data differ from this theory by a factor of ≈1.8, and at 20 MeV by a factor of ≈2.4.

The contrast between the above discrepancy and the excellent agreement which this theory gives with the observed straggling of fully stripped 5.5-MeV α particles[20] suggests that charge-exchange, as discussed by Vollmer[15] and others[7-11] (see Sec. I) might reconcile the apparent difference between theory and experiment in the case of the ^{16}O ions. We therefore proceed to consider this effect for ^{16}O ions with energies ≥20 MeV, while making the initial assumption that the component of the straggling arising from collisional excitation and ionization is correctly represented by the Bethe-Livingston theory, as it is in the case of the fully stripped α particles.

B. Charge-exchange straggling

We first review briefly the theory of charge-exchange straggling given by Vollmer.[15] If the mean free path for charge exchange is greater than the mean free path for a typical collisional energy transfer to a target atom, one may treat the stopping power as constant along the path traveled while the ion is in one of its various charge-states. The calculation of the fluctuation in energy loss due to charge exchange involves a calculation of the fluctuation in the path length traveled in each charge state. The charge-exchange straggling can be obtained analytically when there are only two charge states, and in the general case of several charge states a Monte Carlo calculation is possible. In all cases we require the charge-exchange cross sections in order to carry out these computations.

The procedure for the Monte Carlo calculations is as follows: One assumes the relation for stopping power to be

$$-\frac{dE}{dx}=Kz^2NZB(Z,v)\,, \qquad (1)$$

where $K=4\pi e^4/mv^2$, m is the electron mass, e its charge, z and v are the charge and velocity of the moving ion, and N and Z the number of atoms per unit volume and the atomic number of the stopping material. The quantity $B(Z,v)$ is the stopping number of the target material. At a given energy and for a particular target, Eq. (1) becomes simply,

$$-\frac{dE}{dx}=z^2C\,, \qquad (2)$$

where the constant C follows from Eq. (1).

Now if the charge-exchange cross sections $\sigma_{q,q+n}$ for $n=\pm1,\pm2,\ldots$, etc., are known, the probability distribution $W_q(x)$ for an ion of charge q to travel a distance x before charge-exchanging can be calculated from the expression

$$W_q(x)=N\sum\sigma_{q,q+n}\exp\left(-N\sum\sigma_{q,q+n}x\right). \qquad (3)$$

The Monte Carlo technique consists of generating a sequence of x using the relation

$$x=(-\ln r)\Big/N\sum\sigma_{q,q+n}, \qquad (4)$$

where r is a random number taken from the rectangular distribution $0<r<1$. The next charge state of the ion is determined by calculating from the corresponding cross sections $\sigma_{q,q+n}$ the different weights for charge-changing by n units of charge. This is done by dividing the interval 0 to 1 into lengths of $\sigma_{q,q+n}/\sum\sigma_{q,q+n}$ and choosing another random number to select one of these intervals and hence its corresponding charge $q+n$ which is to be used next. The energy loss experienced while traveling the distance x before charge-exchanging to $q+n$ is obtained with the appropriate value $z=q$ in Eq. (2). Repetition of this process until the total foil thickness is traversed, taking due care in truncating the last x appropriately, provides the energy loss for one particle. If the energy loss of the particle is small compared to the energe range over which the charge-exchange cross sections vary significantly, these latter can be regarded as constant. The energy-loss distribution is generated by following the path of a large number of particles. The variance of this distribution can then be calculated for comparison with straggling data.

A general feature of charge-exchange straggling can be observed from Monte Carlo calculations. If the number of charge-exchange events is large, the variance of the energy-loss distribution is proportional to the distance traveled and hence the charge-exchange straggling is proportional to the square root of the foil thickness. It follows that one may conveniently extract this foil-thickness dependence by dividing the straggling by $(x_{\text{total}})^{1/2}$. Furthermore the charge-exchange straggling will vary at different incident ion energies due to the energy dependence of charge-exchange cross sections, and also because of the energy dependence of dE/dx. This latter energy dependence, which is included in the Monte Carlo calculations through Eq. (2), may also be factored out. Thus it is useful to define a reduced straggling parameter

$$\omega=\frac{\sigma\sqrt{N}}{(\langle dE/dx\rangle\sqrt{x})},$$

where σ is the standard deviation of the charge-exchange straggling distribution.

C. ^{16}O straggling and charge-exchange

Let us now consider further the ^{16}O straggling data in the light of the charge-exchange theory outlined in Sec. IV B. First we examine the prediction of the dependence of the total straggling on foil thickness, before turning to a consideration of the component of the straggling which may arise from charge exchange alone.

The total straggling is obtained by convoluting the calculated charge-exchange straggling with the straggling due to collisional excitation and ionization, which is derived using in this case the Bethe-Livingston theory with the rms charge on the ion. This procedure assumes that the two sources of straggling are uncorrelated: a reasonable assumption if the mean free path for charge exchange is long compared to that for typical collisional excitation and ionization events of target atoms. As this latter straggling contribution also varies as the square root of the foil thickness (provided $0.01\leq\Delta E/E\leq0.1$),[26] the total straggling should vary in the same way.

Indeed our data for ^{16}O straggling are proportional to the square root of foil thickness, as can readily be seen in Fig. 4. It is worth noting incidentally that if our estimated limits of systematic error arising from foil nonuniformity had been applied to these data the proportionality of the straggling to the square root of foil thickness would have been significantly broken.

An estimate of the component of straggling which may arise from the charge exchange of ^{16}O ions in the Al target was obtained by quadratic subtraction of the Bethe-Livingston values from our experimental straggling values. The results were expressed in terms of the reduced straggling ω, and are shown in Fig. 5.

A direct comparison of these results with a calculation of the expected charge-exchange straggling is not possible since cross-section data for the capture and loss of electrons by ^{16}O ions in Al are not available. However, a comparison can be made with calculations for ^{16}O ions in gas targets for which the required cross-section data are available. In Fig. 5 are also plotted these theoretical values of charge-exchange straggling of ^{16}O ions in Ar and N_2 gases, of thickness well in excess of that required for charge-state equilibrium to be reached. These values were obtained using the measured electron capture and loss cross sections of Macdonald and Martin[28] in Monte Carlo calculations as outlined in Sec. IV B, adopting typically five charge states and up to triple capture and loss cross sections. Uncertainties in these

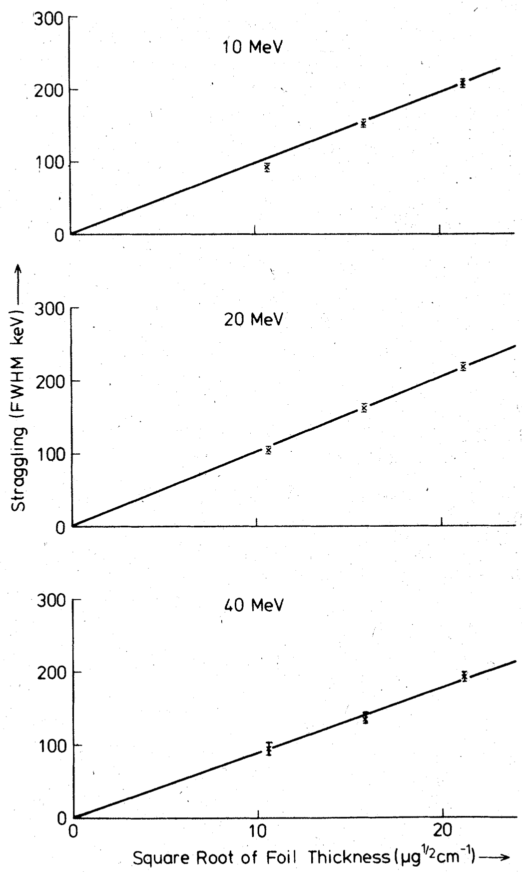

FIG. 4. Variation of ^{16}O straggling, at three different energies vs the square root of the Al-foil thickness. The values were taken from Table I.

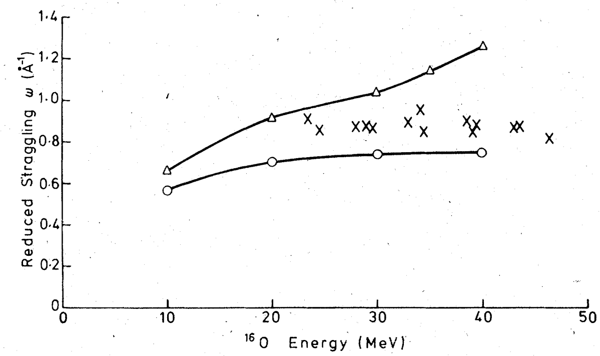

FIG. 5. Measured straggling after quadratic subtraction of the Bethe-Livingston values for ^{16}O in Al(X), and the theoretical charge-exchange straggling for ^{16}O in N_2 (△) and ^{16}O in Ar(0) vs ^{16}O energy.

calculations, which may be as large as 15%, arise partly from the errors in measurement of the cross sections and partly from the error in reading these cross sections from the published graphical data of Macdonald and Martin. The number of particles used in our calculations, typically 2000, implies a standard error on the sample variance of about 3%.

It can be seen from Fig. 5 that the component of straggling attributable to charge-exchange fluctuations in our data for ^{16}O traversing an Al target lies between the values of charge-exchange straggling calculated for ^{16}O ions passing through N_2 and Ar gas targets. Thus it appears highly plausible that charge exchange is indeed responsible for the excess straggling observed with partially stripped ^{16}O ions in Al.

D. ^{16}O charge-exchange cross sections

As mentioned in Sec. IV C, a direct computation of the charge-exchange straggling of ^{16}O ions on traversing an Al target is not possible for lack of charge-exchange cross-section data. In view of the qualitative consistency of the straggling results with gas target calculations as illustrated in Fig. 5, it appears worthwhile to carry out the reverse computation which is possible for the case where there are only two charge states to consider and where the ratio of the two cross sections is known from another source. Charge-state distribution data[27] for ^{16}O ions in Al show that above 40 MeV these ions emerge from the Al predominantly in charge states 7^+ and 8^+, with only a small amount of 6^+. If one neglects this 6^+ component (≈13% at 40 MeV) only the two cross sections $\sigma_{8^+\to 7^+}$ and $\sigma_{7^+\to 8^+}$ need be considered. Since at 40 MeV the fractions of 7^+ and 8^+ are equal, it then follows that at that energy $\sigma_{8^+\to 7^+} \approx \sigma_{7^+\to 8^+} = \sigma$, where σ is an unknown parameter. The value of σ was varied in a Monte Carlo calculation until the calculated reduced charge-exchange straggling equaled the value of 0.9 $Å^{-1}$ inferred from the experimental data as shown in Fig. 5. In this way it was found that the charge-exchange cross sections for capture and loss, $\sigma_{8^+\to 7^+}$ and $\sigma_{7^+\to 8^+}$, should be 6×10^{-18} cm^2/atom. The result was the same within the standard error for a choice of ingoing ^{16}O ion charge of either 8^+ or 7^+. These cross sections imply a mean free path for charge exchange of about 300 Å, whereas the mean free path for collisional excitation and ionization of the Al target is estimated from the mean excitation potential[29] to be about 10 Å. Hence the assumption in the Vollmer theory of the independence of charge-exchange events and collisional energy-loss events is consistent with the charge-exchange cross sections obtained.

As anticipated from Fig. 5, the gas-target charge-exchange cross sections for 40-MeV ^{16}O (for Ar, $\sigma_{8^+\to 7^+} \approx 9\times10^{-18}$ cm^2/atom and $\sigma_{7^+\to 8^+} \approx 4\times10^{-18}$ cm^2/atom; and for N_2, $\sigma_{8^+\to 7^+} \approx 4\times10^{-18}$ cm^2/atom and $\sigma_{7^+\to 8^+} \approx 2\times10^{-18}$ cm^2/atom) are quite close to the result we have inferred for a solid-

Al target of intermediate Z.

Considering now the 13% 6^+ fraction previously neglected, an estimate of the appropriate charge-exchange cross-sections from 6^+ to 7^+ and 7^+ to 6^+ can be made with the guidance of Macdonald and Martin's gas-target data. When this contribution is included in our Monte Carlo calculations the cross sections $\sigma_{7^+\to 8^+}$ and $\sigma_{8^+\to 7^+}$ have to be increased by 30% to 8×10^{-18} cm^2/atom.

V. SUMMARY AND CONCLUSIONS

In our analyses we first noted that, with fully stripped (5.5-MeV) α particles, experimental data for the average energy-loss rate dE/dx and for the energy-loss straggling, are in good agreement with, respectively, the Bethe theory for dE/dx and the corresponding Bethe-Livingston theory for straggling.[20] We then proceeded to extend the theories to a case of partially stripped ions with velocities compatible with the requirements of the theoretical approximations. For energy loss calculations the approach is well known.[1-4] The Bethe theory is assumed to hold providing the square of the nuclear charge is replaced in the formula by a mean-square effective charge which takes account of the screening of the nuclear charge by bound electrons. Indeed in the case we are considering, that of transmission through an Al foil of ^{16}O ions with energy $\geqslant 20$ MeV, experimental measurements of dE/dx (Ref. 22) are represented by the Bethe formula for a value of the mean-square effective charge which is quite close to the measured value of the mean-square charge of the ^{16}O ions after emergence from the foil. This consistency is very satisfactory since near equality of the mean charge inside and external to the stopping medium is expected for ^{16}O ions at high velocities ($v > zv_0$).[4,30]

It is therefore reasonable to extend the Bethe-Livingston straggling theory to partially stripped ^{16}O ions in the same way, using values of the mean-square charge obtained from charge-distribution data. We unfolded from our experimental straggling measurements these theoretical values for the collisional straggling, and proceeded to consider the residual components in terms of charge-exchange straggling. A comparison was possible with calculations which could be made in the manner described by Vollmer for ^{16}O ions in nitrogen and in argon, the required charge-exchange cross sections being available in these two cases. The component of straggling due to charge-exchange for ^{16}O in Al extracted from our data lay between the N_2 and Ar calculations in a consistent manner over the whole energy range from 20 to 40 MeV. We then took the special case of nearly fully stripped ^{16}O ions and extracted from the experimental data a value for the near-equal cross sections for charge exchange between O^{8+} and O^{7+}, obtaining the result $\sigma_{8^+\to 7^+} \approx \sigma_{7^+\to 8^+} \approx 8\times 10^{-18}$ cm^2/atom for 40-MeV-^{16}O ions in Al, with an uncertainty of about 20% due to the small 6^+ charge state fraction. This result was again consistent with cross sections measured in N and Ar.

Thus a consistent overall interpretation of our straggling data has been obtained, giving plausible confirmation of the initial assumptions, namely, that the observed straggling is largely due to collisional straggling, represented by the Bethe-Livingston theory, together with charge-exchange straggling as proposed by Vollmer and others.

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