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RESONANT COHERENT EXCITATION (RCE) OF HIGHER-ORDER RESONANCES FOR $^{28}Si^{13+}$ IONS CHANNELED IN A THIN Si CRYSTAL

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Abstract

Resonant coherent excitation of hydrogen-like $^{28}Si^{13+}$ ions, channeled in a thin Si crystal, has been observed for Δn=1, 2 and 3 transitions (K-shell to L-, M- and N-shells, respectively). In addition, selection of ions which come close to the string, permitted observation of the Stark splitting of the $2s2p_x$ state of the Δn=1 resonance.

INTRODUCTION

When an ion of velocity v passes through a crystal channel with lattice spacing d it experiences a periodic perturbation. If the frequency, $\upsilon = v/d$, of this perturbation corresponds to an atomic or nuclear excitation, $E=h\upsilon$, of the moving ion, then resonant coherent excitation (RCE) can occur. Since the periodic potential experienced by the moving ion consists of sharp maxima in the electric field, and thus contains many harmonics of the fundamental string frequency, the general expression becomes $E=k(h\upsilon)$ where k is an integer.

Detailed studies of RCE for hydrogen-like ions from B to F have been made[1,2] for transitions with $\Delta n=1$, i.e., K- to L-shell transitions and for k values from 1[2] to 6[1]. It was shown that the energy levels of the moving ion differ measurably from the vacuum states. This difference reflects the influence of the static crystal field in removing the degeneracy of the $2p_x$, $2p_y$ and $2p_z$ orbitals and in Stark mixing the 2s and 2p states. Recently, RCE measurements have been made for ^{24}Mg ions in which the K_α decay x-rays have been observed as well as the reduction in frozen charge state fraction[3,4]. In the most recent experiment[4], the alignment of the excited state was determined by measuring x-rays at 90° and 45° to the beam.

In the present work we report the first RCE measurements of $\Delta n=1,2$ and 3 (K- to L-, K- to M- and K- to N-shell) transitions for the case of hydrogen-like $^{28}Si^{13+}$ ions channeled along the <111> and <112> directions in a thin Si crystal. In particular, this is the first time that the $\Delta n=2$ and 3 transitions have been observed. For high-Z ions, the inner-shell electrons of the projectile are strongly localized and only weakly perturbed by the crystal field. Since Si is the heaviest projectile used to date in RCE measurements, very sharp RCE resonances are expected. Through cuts on the energy-loss spectra, we selected particles which interacted strongly with the crystal and wake potential fields, leading to Stark splitting of the $2s2p_x$ state for the $\Delta n=1$ transition.

EXPERIMENT

We obtained the $^{28}Si^{13+}$ beam by stripping and degrading a 27*A* MeV $^{28}Si^{12+}$ beam from the TASCC cyclotron. The Al degrading foils ranged in thickness from 3 mg/cm^2 to 50 mg/cm^2. A narrow momentum range for the 13^+ charge-state component of the degraded beam was selected with the 90° and 18.5° beam-transport magnets downstream of the degrader foil. A beam of low angular divergence was obtained by collimation with two 0.5-mm apertures separated by 3.2 m directly ahead of the scattering chamber.

A thin (~5 μm) Si crystal with a <111> axis normal to its surface was mounted on a 3-axis goniometer. We aligned the crystal using the ratio of the transmitted 13^+ charge state to the sum of 13^+ and 14^+ charge states. At each energy, the spectra of transmitted 13^+ and 14^+ ions were measured in two resistive-wire counters positioned in the focal plane of the Chalk River Q3D magnetic spectrometer for the crystal aligned to the <111> axis. Measurements were made between 20.8 and 26.5*A* MeV for <111> alignment and, separately, between 20.0 and 24.0*A* MeV for <112> alignment. After every fourth or fifth measurement, spectra were measured for random orientation and the crystal alignment was checked.

Figure 1 shows position spectra for transmitted 13^+ and 14^+ ions plotted as a function of the fraction of random energy loss for channeling along the <112> axis. Data are shown for two energies, 21.4*A* MeV (centre of the k=5, $\Delta n=1$ resonance) and 22.0*A* MeV (off resonance). The data for the two energies have been scaled to the same number of incident ions. In addition, the spectra for random alignment are also shown but have been arbitrarily normalized. The direct beam had a FWHM of approximately half the width of the peak in random alignment. Inspection of Figure 1 also shows that only well-channeled 13^+ ions (small fraction of random energy loss) survive transmission through the crystal, while a much wider energy range of 14^+ ions is observed. In random alignment, the equilibrium charge-state fraction for 13^+ ions is only ~6%. Figure 1 also shows that more ions are transferred from the 13^+ charge state (of the beam) to the 14^+ charge state on-resonance than off-resonance as expected since, on-resonance, the 13^+ ions resonantly excited to the L-shell have a lower binding energy relative to the K-shell ground state and thus are more easily ionized. In addition, it can be seen that the more poorly channeled ions (large fraction of random energy loss), which experience a stronger field and are travelling through a region of higher electron density, have a higher probability of being resonantly excited.

RESULTS

Figures 2 and 3 show the surviving fraction of 13^+ ions exiting the crystal for channeling along the <111> and <112> directions, respectively. The error bars shown are based solely on counting statistics. For both axes, the $\Delta n=1$ and $\Delta n=2$ transitions are clearly observed. In both figures the inset shows the region of the expected $\Delta n=3$ transition with expanded vertical and reduced horizontal scales. As can be seen, the width of the $\Delta n=3$ transitions are approximately twice that of the $\Delta n=1$ and 2 transitions. Assuming simple Bohr scaling (n^2/Z) for electronic shell radii the N-shell radius for the moving ion is almost twice that of the M-shell and, for Si, extends well into the region of large electron density regardless of where it is formed in the channel. This results in a greatly reduced lifetime for ions excited to the N-shell and hence an increase in the transition width.

To examine the effect of position in the channel on the RCE process we set windows on the 13^+ and 14^+ spectra for the same fraction of random energy loss and plotted the surviving 13^+ fraction as a function of energy. Figure 4 shows the results of such an analysis for relatively well-channeled ions (0.40 - 0.46 of random energy loss) and for poorly-channeled ions (0.57 to 0.63 of random energy loss), along the <112> axis in the region of the k=6, $\Delta n=2$ and k=5, $\Delta n=1$ resonances; the energy-loss windows used are shown in Figure 1. For well-channeled ions the resonances are weak and narrow as would be expected qualitatively, since the ions are well away from the strings and hence experience a much lower electric field; they are also travelling through a region of reduced electron density. The poorly-channeled ions, on the other hand, experience a much stronger field and greater electron density since they are moving much closer to the atomic strings. This results in greater probability for RCE and a rapid subsequent ionization.

As seen in the lower portion of Figure 4, there is a strong splitting of the resonance for particles with high energy loss. This can be understood as a Stark splitting of the 2p2s states due to the transverse field from the axial crystal potential. There is also a splitting from the stopping (or wake) field but this is smaller by more than an order of magnitude.

In a constant electric field E in the x direction, the splitting of the 2s2px state is $\pm 3eEa_0/Z_1$, where a_0/Z_1 is the Bohr radius for the projectile[5]. We can estimate the strength of the field near the minimum distance of approach, r_{min}, from Lindhard's standard string potential,

$$U(r)=(Z_1Z_2e^2/d)\log((Ca/r)^2+1), \tag{1}$$

and obtain for the average electrostatic field at distance r,

$$E(r) = (Z_2e/rd)2(Ca)^2/((Ca)^2+r^2), \tag{2}$$

where Z_2 is the atomic number of the crystal, d the spacing of atoms along the axis, a the Thomas-Fermi screening radius and C a constant, $C=\sqrt{3}$.

We may estimate the distance r_{min} from the fraction F of particles with higher energy loss in the selected window (see Figure 1). Since F should be approximately equal to the fraction of the incident particles hitting the surface at a distance $r<r_{min}$ to a string, $F=Nd\pi r_{min}^2$, where N is the atomic density in Si. For F=0.2 we obtain r_{min}=0.44 Å. Inserting this value into Eq.(2) we obtain eE=59 eV/Å and the shifts become about ±7 eV.

In the lower part of Figure 4, an asymmetric broadening towards lower energy is seen, corresponding to a shift in resonance energy of about 0.5%. The reason for this asymmetry is discussed in Reference 4 for the analogous planar case. The RCE is strongest for the transition to the $2s2p_x$ state with the intensity lobe towards the maximum of the crystal potential ($2s2p_x(w)$ in Reference 4) and since the string potential is attractive for the bound electron, this is the state with lower energy. A shift of 0.5% corresponds to 10 eV which is close to our estimate above. Since the intensity of the wave function is shifted towards the string by about $3a_0/Z_1 = 0.1$, the effective field at r_{min} is in fact expected to be somewhat larger than calculated above. For $r = r_{min} - 3a_0/Z_1$ we obtain from Eq.(2) a field of about 100 eV/Å.

SUMMARY

We have observed $\Delta n=1$, 2 and 3 transitions for $^{28}Si^{13+}$ ions, channeled along the <111> and <112> axes in a thin Si crystal, as a reduction in the frozen charge-state fraction. This is the first time the $\Delta n=2$ and 3 transitions have been clearly resolved in RCE experiments.

By putting windows on the energy-loss spectra we were able to select ions which move close to the atomic strings. Because these ions experience a much stronger electric field from the axial crystal potential, we were able to observe Stark splitting of the $2s2p_x$ state for the $\Delta n=1$ resonance.

ACKNOWLEDGEMENTS

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REFERENCES

1. C.D. Moak, S. Datz, O.H. Crawford, H.F. Krause, P.F. Dittner, J. Gomez del Campo, J.A. Biggerstaff, P.D. Miller, P. Hvelplund and H.F. Knudsen, Phys. Rev. A19 (1979) 977.

2. P.D. Miller, H.F. Krause, J.A. Biggerstaff, O.H. Crawford, S. Datz, P.F. Dittner, J. Gomez del Campo, C.D. Moak, N. Neskovic and P.L. Pepmiller, Nucl. Instr. and Meth. B13 (1986) 56.

3. S. Datz, P.F. Dittner, J. Gomez del Campo, K. Kimura, H.F. Krause, T.M. Rosseel, C.R. Vane, Y. Iwata, Y. Honda, Rad. Eff. and Def. in Solids 117 (1991) 73.

4. S. Datz, P.F. Dittner, H.F. Krause, C.R. Vane, O.H. Crawford, J.S. Forster, G.C. Ball, W.G. Davies and J.S. Geiger, to be published in Nucl. Instr. and Meth.

5. H.E. White, Introduction to Atomic Spectra (McGraw-Hill, New York and London, 1934).

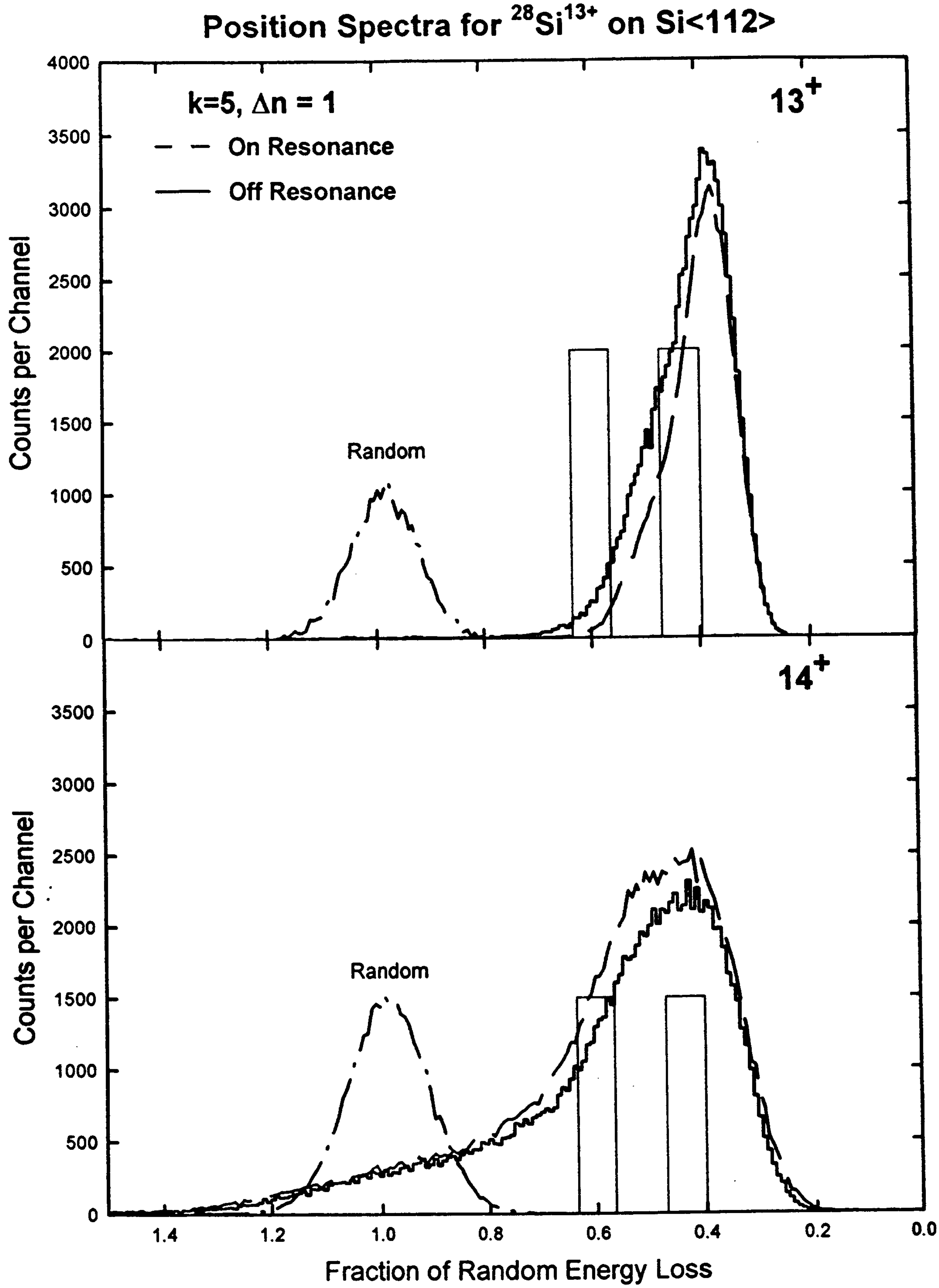
FIGURE CAPTIONS

Figure 1 Position spectra of 13^+ and 14^+ ions transmitted through the crystal for incident energies of 22.0 (—) and 20.4 (- -) *A* MeV plotted as a fraction of random energy loss. The aligned, <112>, spectra have been normalized to the same number of incident ions. The spectra for random alignment (- • -) have been arbitrarily normalized. The two windows selected in Figure 4 are marked by histograms.

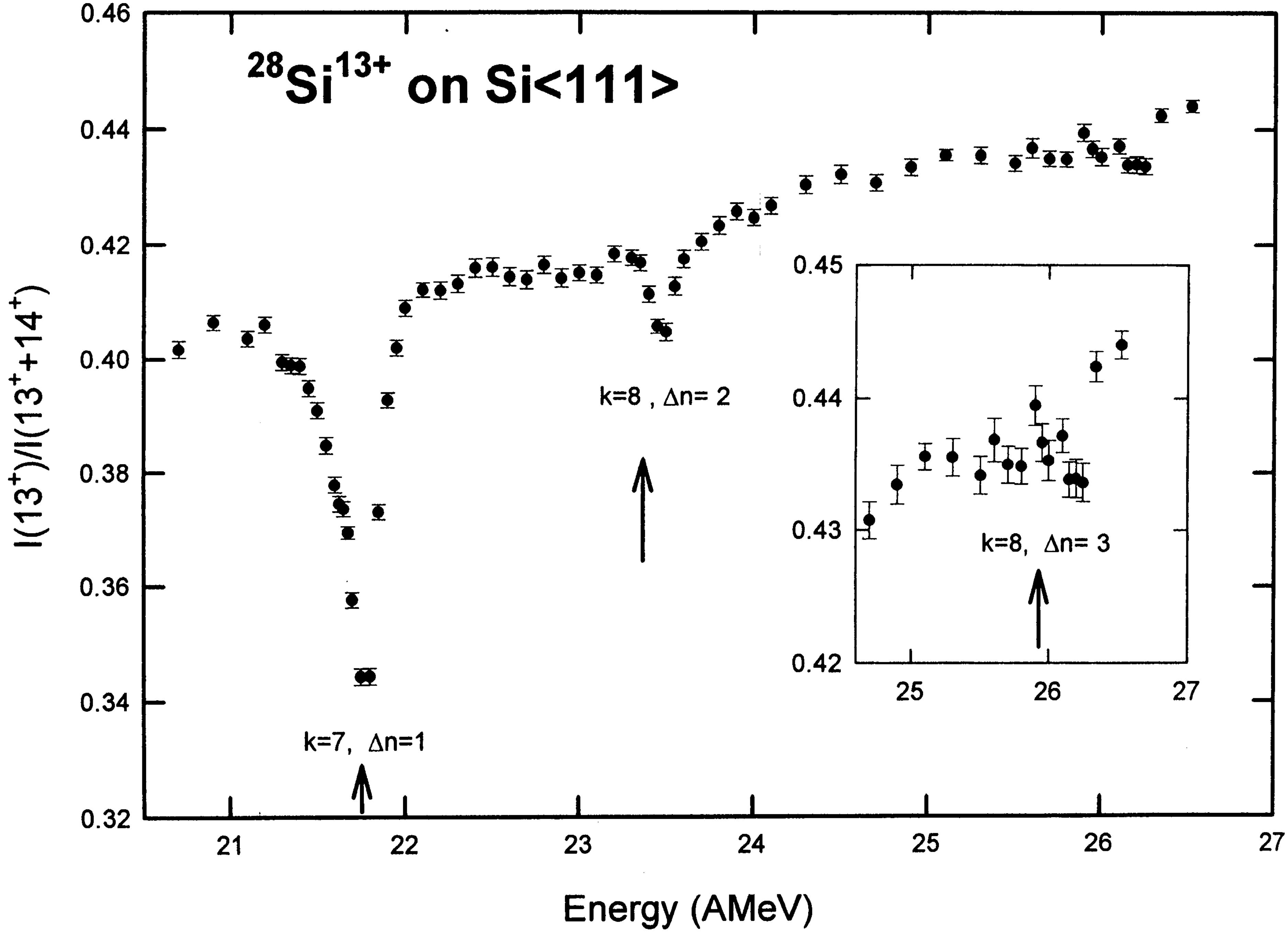
Figure 2 Energy dependence of the fraction of 13^+ ions to (13^+ + 14^+) ions transmitted through the crystal along the <111> direction. Predicted resonance energies are indicated by arrows.

Figure 3 Same as Figure 2 but for the <112> direction.

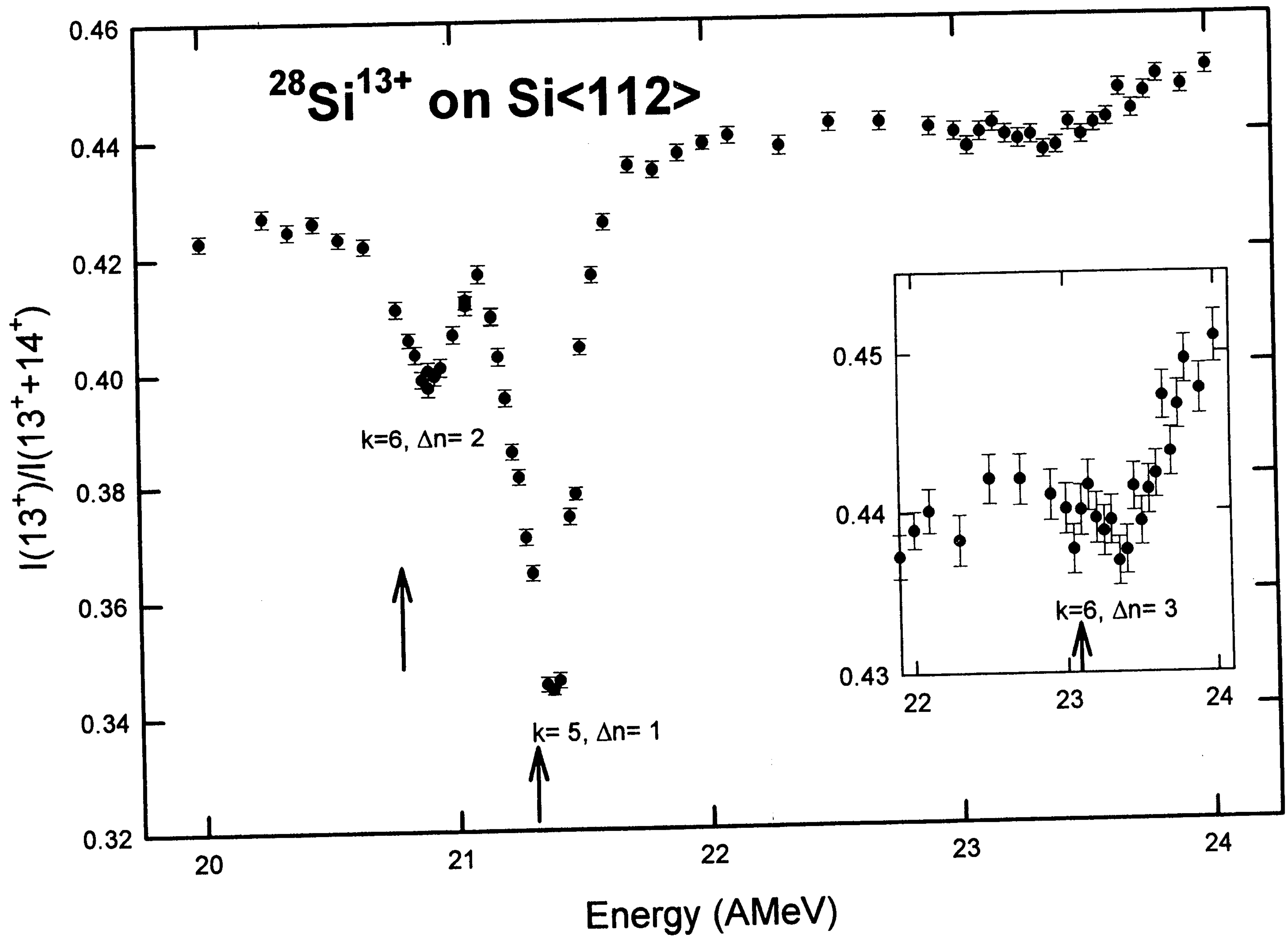
Figure 4 Same as Figure 3 but for windows on the energy loss. The two windows are shown in Figure 1.



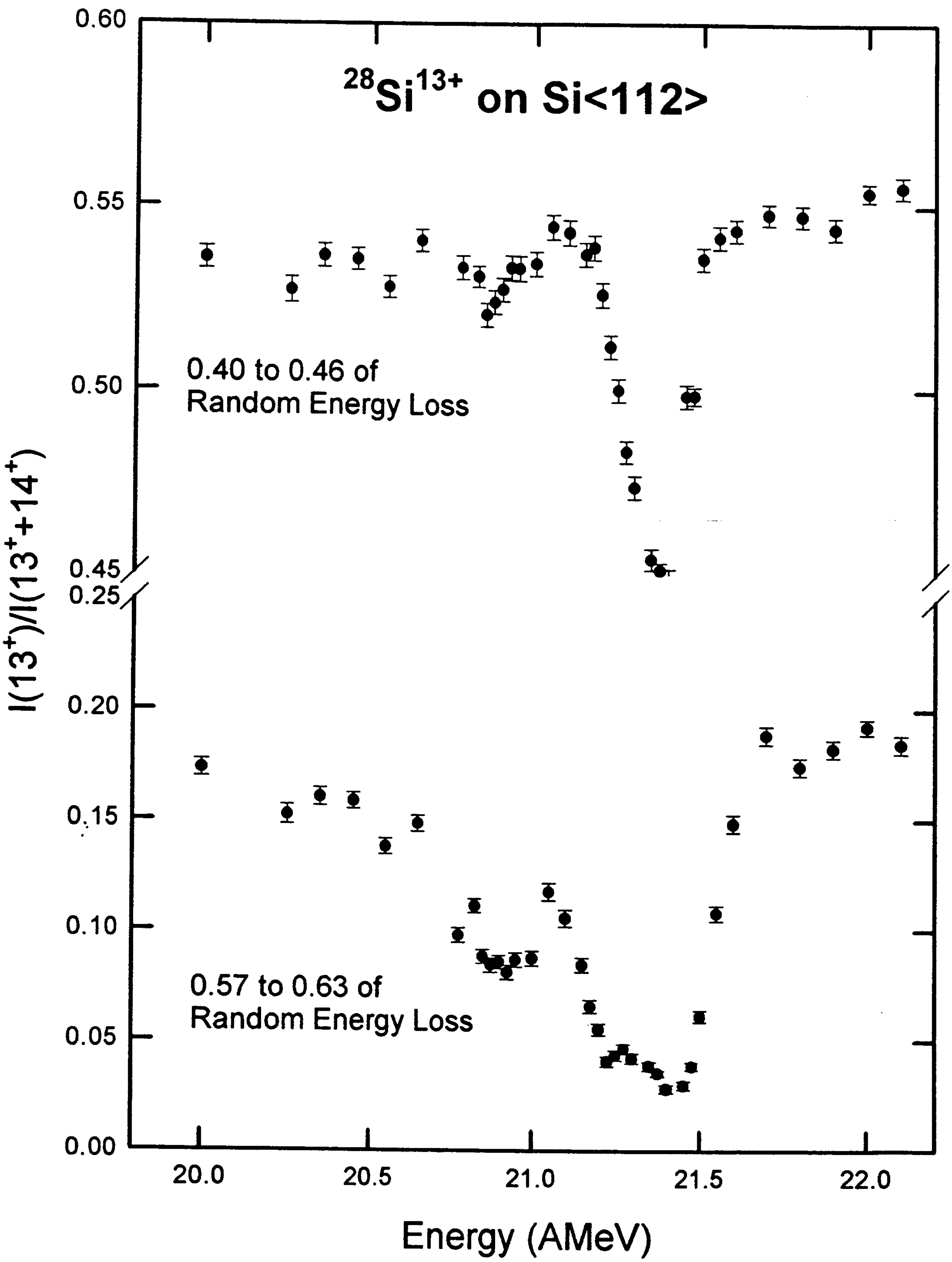
Position Spectra for 28Si13+ on Si<112>
k=5, Δn = 1
13+
On Resonance
Off Resonance
Random
14+
Random
Counts per Channel
Counts per Channel
Fraction of Random Energy Loss
4000
3500
3000
2500
2000
1500
1000
500
0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0



$^{28}Si^{13+}$ on Si<111>
I(13+)/I(13+ + 14+)
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
21
22
23
24
25
26
27
Energy (AMeV)
k=7, Δn=1
k=8 , Δn= 2
k=8, Δn= 3
0.45
0.44
0.43
0.42
25
26
27



$^{28}Si^{13+}$ on Si<112>
$I(13^+)/I(13^++14^+)$
Energy (AMeV)
k=6, Δn= 2
k= 5, Δn= 1
k=6, Δn= 3
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
20
21
22
23
24
0.45
0.44
0.43
22
23
24



$^{28}Si^{13+}$ on Si<112>
0.40 to 0.46 of
Random Energy Loss
0.57 to 0.63 of
Random Energy Loss
$I(13^+)/I(13^+ + 14^+)$
Energy (AMeV)
0.60
0.55
0.50
0.45
0.25
0.20
0.15
0.10
0.05
0.00
20.0
20.5
21.0
21.5
22.0