Search for a narrow resonant transfer and excitation resonance of titanium projectiles channeled in a gold crystal

P. F. Dittner, C. R. Vane, H. F. Krause, J. Gomez del Campo, N. L. Jones, P. A. Zeijlmans van Emmichoven, U. Bechthold, and S. Datz
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
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Transfer and excitation, resulting from simultaneous electron capture and K-shell excitation in a single collision, has been measured 280–310-MeV Ti^{20+} ions channeled in the $\langle 100 \rangle$ axis of a thin Au single crystal. The 19+ charge-state fraction of the Ti ions exiting the Au crystal was measured as a function of ion energy and showed no narrow peak attributable to resonant transfer and excitation (RTE). The number of Ti $K\alpha$ x rays, emitted by the Ti ions due to RTE, in coincidence with Ti^{19+} was also measured at two energies, on and off the previously reported narrow resonance, and again no evidence for a narrow resonance was observed.

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I. INTRODUCTION

Dielectronic recombination [1] (DR) is a process in which a free electron excites a bound electron on an ion, is itself captured, and then the doubly excited state is stabilized via photon emission. Since a doubly excited intermediate state of the ion is required, DR is a resonant process having a very small energy width [2]. DR has been studied in merged electron- and ion-beam [3] configurations and in electron-beam–stationary-ion-target [4] arrangements. In each case the widths of the observed resonances are determined by the velocity spread of the electron beam.

Resonant transfer and excitation [5] (RTE) is a closely related process where the role of the initially free electron of the DR process is played by a loosely bound target electron. In these experiments a high-energy ion beam collides with a stationary gas molecule. In the absence of any motion of the target electron, one would observe a very narrow resonance at an ion energy given by the ratio $(M/m)E_e$, where M and m are the mass of the ion and electron, respectively, and E_e is the required electron energy for the DR resonance. In reality, since the electrons in the target atom or molecule have a considerable spread in their velocities, given by their Compton profile, the resonance width is a significant fraction of the ion-beam energy.

Several previous heavy-ion channeling studies [6–9] have demonstrated that the ions avoid most hard collisions and interact primarily with loosely bound electrons. In particular, Datz *et al.* [10] have demonstrated RTE by observing the x rays emitted by the doubly excited ions while channeling S^{15+}, Ca^{19+}, Ti^{20+}, and Ti^{21+} ions through silicon crystals. In these experiments strong peaks in x-ray yields for hydrogen- and heliumlike ions were found near projectile energies corresponding to RTE resonances. The widths of the resonances expressed in ion energy were determined by an analog of the Compton profile, the Fermi energy of the electrons near the channel center. It has been shown [11] that treating the electrons in a crystal channel as an electron gas yields consistency among the magnitude and width of the RTE resonance, the magnitude and width of the radiative-electron-capture peak, and the energy loss of the channeled ions. Knowledge of the electron density and the crystal thickness yielded an electron-target thickness which in turn gave RTE cross sections [11] which agree very well with RTE cross sections derived from gas targets [12].

Recently Belkacem *et al.* [13] performed a similar experiment to that of Datz *et al.* [10] with some notable differences in experimental procedure and even more notable differences in their results. Belkacem *et al.* channeled Ti^{19+} and Ti^{20+} ions through the $\langle 110 \rangle$ axis of a 1200-Å-thick Au crystal; Datz *et al.* channeled Ti^{20+} ions through the $\langle 110 \rangle$ axis of a 2.6-μm-thick Si crystal. Whereas the latter measured the K x rays of Ti in coincidence with the Ti^{19+} ions exiting the crystal scattered through angles less than 0.5 mrad, Belkacem *et al.* measured only the 19+ charge-state fraction but "isolated the best-channeled ions through high-resolution measurements of their energy losses." The high-resolution energy measurements were accomplished by detecting the channeled ions with a position-sensitive parallel-plate avalanche detector positioned in the focal plane of an Enge split-pole magnetic spectrograph. The analysis of their data yielded a narrow resonance where "The observed peak widths are at least 5 times narrower than any previously observed for RTE." Applying the same logic as above, i.e., that the RTE width is related to the Fermi energy which is in turn related to the electron density, one obtains an electron density equal to $8.5\times10^{19}/cm^3$, which is much lower than the generally accepted [14] interstitial density of $2.0\times10^{23}/cm^3$. The solution to this dilemma would obtain if the simple Fermi relationship between electron density and electron momentum distribution were not valid. We thought it necessary to check this remarkable observation.

II. EXPERIMENTAL ARRANGEMENTS

The Ti^{20+} beam was supplied by the 25URC tandem accelerator of the Holifield Heavy Ion Facility at Oak Ridge National Laboratory. The ion-beam energy was stepped from 280 to 310 MeV to cover the energy region of the previously reported resonance. The ion beam was collimated by two circular apertures having diameters of 1 and 0.5 mm, located 2.1 m and 22 cm, respectively, from the Au crystal (see Fig. 1). These apertures collimated the ion beam to 0.4-mrad divergence. This collimation was more than ten times narrower than the channeling half-angle for Ti ions in the $\langle 100 \rangle$ axis, $\psi_1 = 6.45$ mrad. By measuring the energy loss of alpha particles from a ^{244}Cm source and using the stopping power values of Andersen and Ziegler [15], we determined the thickness of the Au crystal to be 1520 ± 70 Å. The Au crystal, which has the $\langle 111 \rangle$ axis normal to its surface, was mounted in a two-axis goniometer. The crystal normal was rotated by 54.74° with respect to the ion-beam axis and aligned by visually observing the channeling pattern on a ZnS-coated surface located downstream from the goniometer. That the ions were traversing the $\langle 100 \rangle$ axis was determined from the angle with respect to the $\langle 111 \rangle$ axis and the visual observation of the pattern in this vicinity. Visual differences of the channeling pattern can be observed for tilts (near the crystal axis) on the order of 0.01°. A Si(Li) x-ray detector was located ~ 3 cm from the crystal with its axis at 45° with respect to the ion beam axis. This detector had a resolution of 200-eV full width at half maximum (FWHM) at 5.9 keV, and a collection and detection efficiency of 1×10^{-3}. In measurements to determine the charge-state fractions, the ion beam transmitted by the crystal passed through another 1-mm-diam circular aperture 50 cm downstream from the crystal before entering the Enge magnet. Thus ions deflected by more than 1.5 mrad (i.e., about $\frac{1}{4}$ the channeling half-angle) were not energy analyzed. A two-dimensional position-sensitive channel-plate detector (2DPSD) was located in the focal plane of the Enge magnet to indicate both the vertical scattering angles and final energies of the channeled ions. The position resolution of the 2DPSD was 0.15 mm, which corresponded to an energy resolution of 50 keV. The associated electronics and the data-acquisition system facilitated the storage of two-dimensional ion-position spectra, x-ray spectra and coincidence (ion–x-ray) spectra. The data were stored in list mode on tape to allow off-line sorting of various parameters.

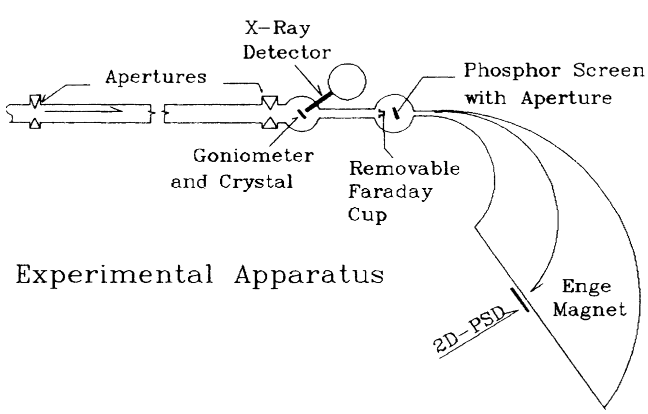

FIG. 1. Sketch of the apparatus. The Ti ions enter the apparatus from the left and terminate their flight at the focal plane of the Enge magnet (2D-PSD means a two-dimensional position-sensitive channel-plate detector).

III. PROCEDURE AND ANALYSIS

With the crystal retracted from the ion beam, 280-MeV Ti ions were steered through the apertures and onto the 2DPSD. From the width of the peak, the resolution of the detector and the geometric size of the beam, we derive the spread of the initial energy, $E_0 = 110 \pm 20$-keV FWHM. The magnetic field was then changed in small steps to produce a series of peaks across the detector. From a least-square fitting procedure of these peak positions and the known fields as measured by an NMR probe, we arrived at a calibration relating the field, position, and energy for all subsequent measurements. The Au crystal was inserted and the goniometer adjusted to channel the Ti^{20+} ion beam through the $\langle 100 \rangle$ axis. The crystal was not removed after this adjustment. The field of the Enge magnet was adjusted to have one of the exiting charge states q_f impinge on the 2DPSD, while at the same time counting x rays with the Si(Li) detector. The procedure was carried out at each E_0 for $q_f = 21+, 20+, 19+$, and $18+$. The energies E_0 ranged from 280 to 310 MeV to cover the region where the sharp resonance of Ref. [13] was observed. The number of Au M x rays, Ti $K\alpha$ x rays, and Ti $K\beta$ x rays was used to normalize the number of ions having q_f to the number of incoming Ti^{20+} ions. This entire procedure was repeated for the same values of E_0 and q_f with the crystal oriented such that the ions traversed a random direction having the same thickness as when channeled.

An energy-loss spectrum of ions with $q_f = 19+$ transmitted in a random direction of the crystal at 293 MeV is shown in Fig. 2. The mean random energy loss E_r equal to 2.67 MeV has a width of 0.48-MeV FWHM. The energy-loss spectrum for channeled ions having the same E_0 and q_f is shown in Fig. 2. The channeled energy loss at the peak of the distribution is 1.09 MeV. The mean energy loss is 1.15 MeV and the peak width is 0.82-MeV FWHM. Here, as in previous works [6], the energy loss (peak or mean) of well channeled ions is less than 50% of the random energy loss. No sharp structures were observed in the energy spectrum of the channeled ions at any E_0, contrary to the observations of Belkacem *et al.* It should be pointed out, however, that the acceptance angle of the channeled ions of this work is much smaller than that of Ref. [13], being 1.5 mrad vs 4°. We made two arbitrary cuts in the spectra of channeled ions corresponding to $E_f = 0.4E_r$ and $0.5E_r$. Since few if any channeled ions lost less energy than $0.3E_r$, cuts at less than $0.4E_r$ resulted in a statistically small sample having large error bars and thus the results were deemed to be too unreliable to determine meaningful charge state

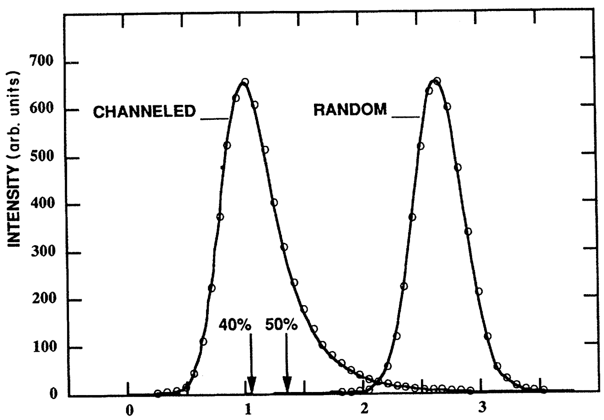

FIG. 2. Energy-loss spectrum of channeled ions (peak at 1.09 MeV) and ions traversing the Au crystal in a random direction (peak at 2.67 MeV). The location of the energy cuts made at $0.4E_r$ and $0.5E_r$ are shown as arrows on the abscissa.

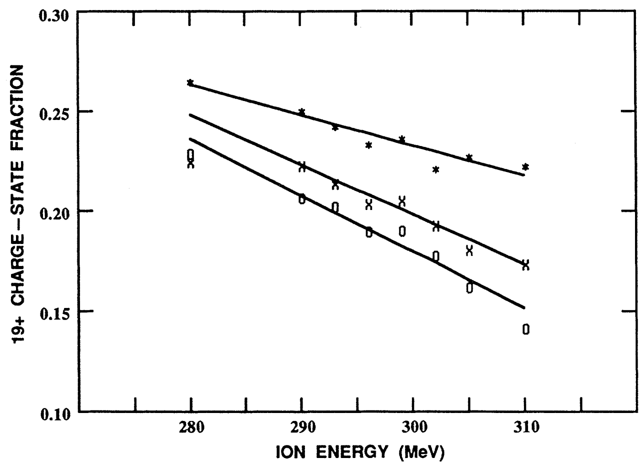

FIG. 3. The Ti^{19+} charge-state fraction for all (∗), better (X), and best (0) channeled ions (see text) vs ion energy. The straight lines through the points are the results of linear least-square fits to the data points. The vertical extent of the symbols in this figure and Figs. 4 and 5 represents the statistical error bars of the data.

fractions. The positions of these cuts are indicated in Fig. 2. Using this procedure we generated three groups: all (any E_f), better ($E_f < 0.5E_r$), and best ($E_f < 0.4E_r$) channeled ions at all E_0 and all q_f. The 19+ charge-state fraction for all, better, and best channeled ions versus energy is shown in Fig. 3. The points are plotted along the abscissa at the respective E_0 rather than at $(E_0+E_f)/2$ since it is not clear which E_f, peak or mean, to use and since a shift of about 0.6 MeV would hardly be noticeable on this energy scale. No peak, including any sharp peak, occurs at or about $E_0=295$ MeV in any one of the three energy groupings. Instead there is a monotonic decrease in the 19+ fraction for all three components as would be expected from the decreasing mechanical or three-body electron-capture cross sections with increasing energy. Mechanical electron-capture processes dominate RTE and radiative capture in this energy regime. The 19+ fraction decreases with decreasing energy loss as would be expected since lower energy loss and better charge-state "frozenness" should be associated with better channeled ions.

We also collected x-ray spectra in coincidence with the 19+ ions on the 2DPSD at $E_0=293$ MeV (on resonance) and at $E_0=305$ MeV (off resonance) with the final aperture removed. We made cuts in E_f corresponding to $\frac{2}{3}$ and $\frac{4}{3}$ of the mean energy loss $\overline{\Delta E}$ of the channeled ions for both E_0 values and extracted the number of Ti $K\alpha$ x rays per incident Ti^{20+} ion in the three energy groups. The results are shown in Table I. Again there is no evidence for a sharp resonance which should appear as a factor of 5–10 increase in the x-ray yield at $E_0=293$ MeV beyond that at $E_0=305$ MeV. The relationship between the x-ray yield and E_f is rather complex, needing a detailed analysis of the ion trajectories, electron densities, and crystal thickness for understanding and will appear in a future publication.

IV. CONCLUSION

We have searched for and not found a sharp RTE resonance for Ti^{20+} ions channeled in a thin Au crystal as has been previously reported by Belkacem *et al.* [13]. The discrepancy in the results is puzzling because both experiments were so similar. Both experiments investigated the Ti^{20+} entrance and Ti^{19+} exit channel in the same energy regime and for a Au target. Both experiments used an Enge split-pole spectrograph for energy analysis of the channeled ions and the angular divergence of the beam was much less than the critical-channeling half-angle in both investigations. Yet when one plots the data from Fig. 4 of Ref. [13] and our data for the 19+ fraction of the best channeled ions (see Fig. 4), the discrepancy is enormous.

The principal difference in the experiments is that our investigation involved channeling along the ⟨100⟩ axis rather than the ⟨110⟩ axis and our crystal was thicker by about a factor of 2. The ⟨100⟩ axis is located at the intersection of two {100} planes and two {110} planes; the ⟨110⟩ axis is at the intersection of two {111} planes, a

TABLE I. Ti $K\alpha$ x-ray yield versus Ti^{20+} energy.

	Ti $K\alpha$ x rays per 10^5 incident Ti^{20+} ions			
	Energy-loss groups			
E_0 (MeV)	$0 < E_f < \frac{2}{3}\overline{\Delta E}$	$\frac{2}{3}\overline{\Delta E} < E_f < \frac{4}{3}\overline{\Delta E}$	$\frac{4}{3}\overline{\Delta E} < E_f$	All E_f
293	0.43±0.03	1.47±0.08	0.28±0.02	2.18±0.11
305	0.53±0.03	1.20±0.08	0.34±0.02	2.07±0.11

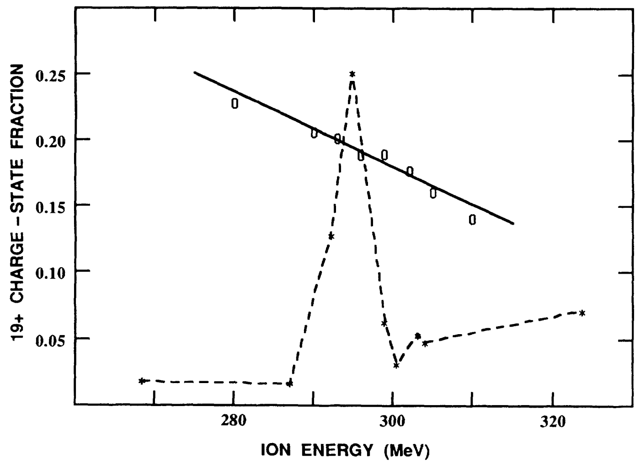

FIG. 4. The 19+ charge-state fractions of the best channeled ions of Ref. [13] (*) and this work (0) vs ion energy. The data of Ref. [13] are connected by a dashed line. The line through the data of this work is the same as in Fig. 3.

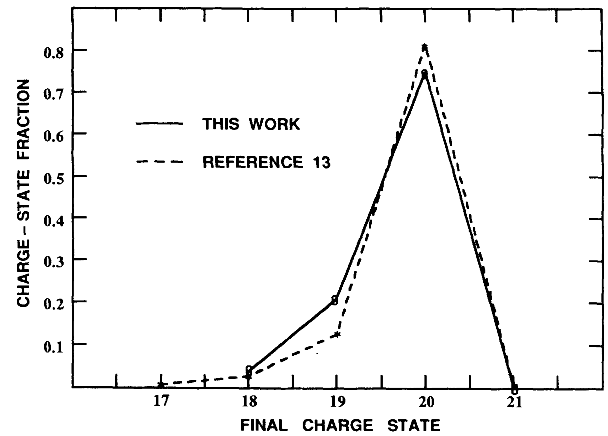

FIG. 5. Exit charge-state fractions for 293-MeV Ti^{20+} channeled along the ⟨100⟩ axis of a 1520-Å-thick Au crystal as measured in this work (0) and the data (*) for well channeled ions from Fig. 2 of Ref. [13].

{110} plane, and a {100} plane. The widths of the {100}, {110}, and {111} planar channels are 2.039, 1.442, and 2.354 Å, respectively. Another difference in the two experiments as mentioned above was the acceptance angle of the energy-analyzed channeled ions. However, since the best channeled ions, i.e., those that have lost the least energy, are also the ones suffering the least angular deflection, the comparison should still be valid. If the effect observed by Belkacem *et al.* is highly dependent on the axial channel chosen, then the RTE process would have to be extremely sensitive to impact parameters. However, since the "size" of the Ti^{19+} ion in an $n=2$ state (~ 0.1 Å) is much smaller than either axial channel, and since choosing low-energy-loss ions implies ions traveling close to the center of the axis, it is difficult to support such an assumption. Alternatively, the effect might be dependent on the distance between atoms along the axial direction. Since the measured charge-state fractions and energy loss normalized to each crystal thickness are so similar, as discussed below, we doubt that either of the latter suggestions are likely.

Another qualitative difference might be the "goodness" of the channeling achieved by the two groups. In Ref. [13], in order to demonstrate channeling quality, charge-state fractions for channeled and random orientations were presented. Figure 5 includes data from Fig. 2 of Ref. [13] with our data points added. It should be noted that the data of Ref. [13] were recorded at an energy near the peak of their resonance. Our comparison is made here because this was the only distribution reported. There is no dramatic difference in the two results and the slightly lower "frozenness" observed in this work is probably due to the ⟨100⟩ axis being slightly narrower than the ⟨110⟩ axis. Considering that our crystal thickness is about twice that of Ref. [13], which would also decrease the amount of frozen charge state, the agreement is excellent. Figure 1(d) of Ref. [13] is a superposition of the random energy-loss distribution (with the peak set arbitrarily at zero) and the channeled energy-loss distribution for $q_f=19+$. Figure 6 is a superposition of data from that figure and our data with our random energy loss scaled to theirs. We assumed that the energy loss of random ions would scale with crystal thickness. The measured random energy loss was 2.67 MeV for a thickness of 2633 Å (=1520 Å/cos 54.7°) and thus for 1200 Å (as reported in Ref. [13]) one derives a random energy loss of 1.22 MeV. Energy losses given relative to the random peak were then converted to a percentage of 1.22 MeV, as displayed in Fig. 6. Ions that have lost the least amount of energy (to the left in Fig. 6) are the best channeled. From this figure, it appears that our best channeled ions are as well

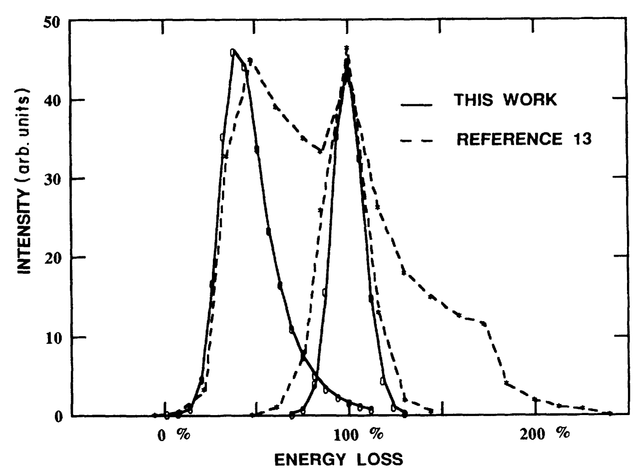

FIG. 6. Channeled and random energy-loss spectrum of ions with exit charge state 19+ plotted as a percentage of the mean energy loss of ions traversing the Au crystal in a random direction. Data of this work (0) scaled to E_r with a solid line connecting the points. Data (*) from Fig. 1(d) of Ref. [13] scaled to the appropriate E_r with a dashed line connecting the points. Both sets of data were taken with a 293-MeV Ti^{20+} ion beam entering the crystal.

channeled as the ions in Ref. [13]. (One would expect that their best channeled ions should appear at an even lower energy loss than ours because the ⟨110⟩ axis is more open than the ⟨100⟩ axis.)

Datz *et al.* [10] also channeled Ti^{20+} ions along the ⟨110⟩ axis of a thin crystal and by measuring the yield of Ti K x rays in coincidence with Ti^{19+}, versus E_0, observed a broad ($\sim$25-MeV FWHM) rather than a narrow ($\sim$5-MeV FWHM) RTE resonance. Although these x rays were not discriminated against with respect to ion energy loss, the angular acceptance of detected ions was restricted to those scattered less than 0.5 mrad. Since, to first order, the best channeled ions are deflected the least, it can be said that these x rays were also in coincidence with the best channeled ions. The only major factor differentiating the result of Datz *et al.* and Belkacem *et al.* is that the former used a 2.6-μm Si crystal and the latter used a $\sim$800-Å Au crystal. The work reported here attempted to overcome this difference by using a thin Au crystal. However we did not observe a narrow RTE resonance in either the charge-state fraction or x-ray yields as a function of ion energy.

Note added in proof. Since acceptance of this manuscript, a possible theoretical explanation has been offered in a paper by J. Feagin and K. Wanser, Phys. Rev. A **44**, 4228 (1991).

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