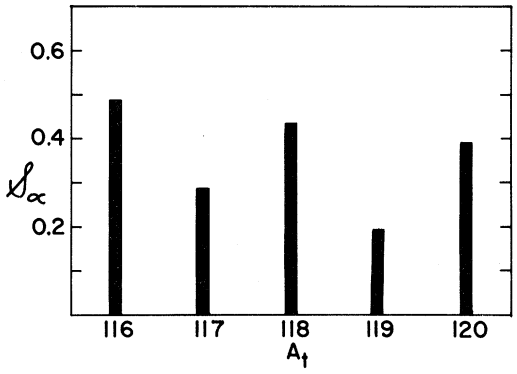

FIG. 3. α-particle spectroscopic factors for Sn(d, ^{6}Li)Cd (g.s.) normalized such that $S_\alpha = 1.0$ for ^{20}Ne(d, ^{6}Li)^{16}O (g.s.) at $E_d = 35$ MeV (Ref. 8).

tions is quite similar to that observed[1] in the (p, t) reaction. This fact is illustrated in Fig. 2 where the integrated (p,t) g.s.$\rightarrow$g.s. cross sections are displayed together with the (d,^{6}Li) data. The close similarity between the α-transfer and two-neutron–transfer data suggests that the two protons transferred in (d,^{6}Li) act primarily as "spectators." It also suggests that $s_{1/2}$ orbitals, as expected,[1,7] are very important in multinucleon-transfer reactions since this is the orbital "blocked" in the odd-A Sn isotopes.[1]

α-particle "spectroscopic factors," S_α, deduced from our data by use of zero-range DWBA are given in Fig. 3. The calculations are normalized such that $S_\alpha = 1.0$ for ^{20}Ne(d,^{6}Li)^{16}O at $E_d = 35$ MeV.[8,9] As anticipated, the S_α values show the same odd-even variation as observed in the cross-section data. While finite-range and other effects may slightly alter the results obtained with the above DWBA calculations and hence the absolute S_α values,[8] they are not expected to change the systematic features shown in Fig. 3.

It is hoped that the study of neutron blocking and related phenomena in (d,^{6}Li) and other α-transfer reactions will provide further insight into the nature of multinucleon-transfer reactions and of clustering in heavy nuclei, and serve as a quantitative test for microscopic theories.

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Evidence for Residual K-Shell Excitation in Chlorine Ions Penetrating Carbon*

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Chlorine ions at 70 and 140 MeV energy impinge upon ~1-μg/cm^2 Cu targets, in one case after emerging from a carbon prefoil and in the second striking Cu on the back side of a carbon foil. The latter approach leads to an appreciable increase in the Cu K x-ray yield, an effect which is explained in terms of residual Cl K-shell excitation and which is in accord with a simple model of competing rearrangement processes.

One of the interesting aspects of the passage of ions through solids is the possibility of residual excitation in the electronic orbitals of the projectile due to collision times which are shorter than de-excitation lifetimes. Such an ion emerges from the solid and de-excites via photon or Au-

ger-electron emission, in the second mode increasing the charge state above that in the solid. Betz and Grodzins[1] suggested that the extent of such excitation in heavy ions moving through solids is sufficient to account in large part for the observation that equilibrium charge-state distributions emerging from foils are centered higher than equilibrium distributions in thin gases. To determine the states of heavy ions in the solid requires the measurement of some quantity sensitive to those states, i.e., to the occupancy of the various projectile shells. With several recent experiments[2] indicating the strong dependence of certain inner-shell-vacancy cross sections on projectile charge state, the observation[3] of x rays is a natural way in which to study the ion-solid interaction.

This Letter presents a measurement of relative Cu K x-ray yields induced by bombardment with 70- and 140-MeV Cl ions prepared in two ways. The first is by passing Cl beams through a 50-μg/cm^2 prefoil prior to their striking ~1-μg/cm^2 Cu targets evaporated onto carbon backings of thicknesses from ~20 to 200 μg/cm^2. The second consists of simply rotating the targets 180° and allowing the beam to pass through the carbon before encountering the Cu. The latter method results in a considerable enhancement in the production of Cu K x rays which increases with increasing carbon thickness and appears to reach a limiting value with the thicker foils. On the basic of a measurement of the cross sections for individual charge states and some simplifying assumptions, the effect can be interpreted as being due to K vacancies in the Cl ions at the time they enter the Cu, a residual K-shell excitation which is surprisingly well predicted by a simple model for K-shell rearrangement processes used recently Betz *et al.*[4] to obtain K transition lifetimes in S ions.

Cl beams of energy 70 and 140 MeV were obtained from the State University of New York at Stony Brook FN tandem Van de Graaf accelerator and the Brookhaven National Laboratory MP (three-stage) tandem Van de Graaf accelerator, respectively. A 38-MeV F beam from the Stony Brook facility was also utilized. The beams passed through a carbon prefoil 24 cm upstream from the target position and were collimated to 0.3 cm before entering the target chamber. A Si(Li) detector with 210-eV resolution for the 5.89-keV Mn $K\alpha$ x ray viewed the targets at 90° to the beam axis through a 0.0012-cm Mylar window, subtending a solid angle of 3.4×10^{-3} sr. A 0.0038-cm-thick Al absorber was used to reduce the Cl K x-ray rate. The target chamber and following beam line constituted the beam dump, all of which was evacuated to ~10^{-6} Torr. Beam integration was accomplished by charge integration, which was normalized to elastic scattering from a 400-μg/cm^2 Au foil placed at the target position into a surface-barrier detector at 90° to the beam. Carbon and copper thicknesses were determined in the same manner with use of 2.0-MeV protons to an absolute accuracy of ~10%.

Runs were made with the Cu targets facing forward 30° off the beam axis, toward and away from the Si(Li), each time followed immediately by a run with the target rotated 180°. In all following discussion the cross section with Cu facing the prefoil is referred to as σ_x^E and the cross section with Cu facing away as σ_x^S. For the foil thicknesses mentioned in this paper, which include the correction for angle, the absorption of Cu K x rays was negligible. Beam currents were kept below ~15 nA and total running time on a particular target was less than 1 h. Possible effects due to carbon buildup in the vicinity of the beam spot were ruled out by repeating with fresh targets and also by the consistency of results with the same target over several runs. Extraction of $K\alpha$ and $K\beta$ yields involved photopeak integration with subtraction of a background determined by a least-squares linear fit to regions on either side of the peaks. The background was significant, ~10% of the Cu x rays, only for the thickest backings.

The Cu K cross sections for individual Cl charge states at 140 MeV, normalized to the value for Cl^{15+}, are shown in Fig. 1. The cross section, insensitive to the L occupation, jumps drastically when a Cl K vacancy is present. The 1 μg/cm^2 of Cu is about one tenth of one mean free path for a 10^{-17}-cm^2 cross section, which is larger than the pickup[5] and loss cross sections[6] estimated here for the Cl K shell in Cu. This indicates that the Cu very nearly satisfies single-collision conditions as far as Cl K rearrangement is concerned, an assertion supported by obtaining essentially the same results for several data points with use of a 2-μg/cm^2 Cu layer. In addition a valuable comparison is available from a recent study[5] of $Cl^{15+,17+}$-Kr collisions at the same energies with a thin gas target. Because of a likeness in Kr and Cu K binding energies, relative cross sections should be in similar proportion. The Kr data suggest that the relative value for Cl^{16+} in Fig. 1 is just about what would be ex-

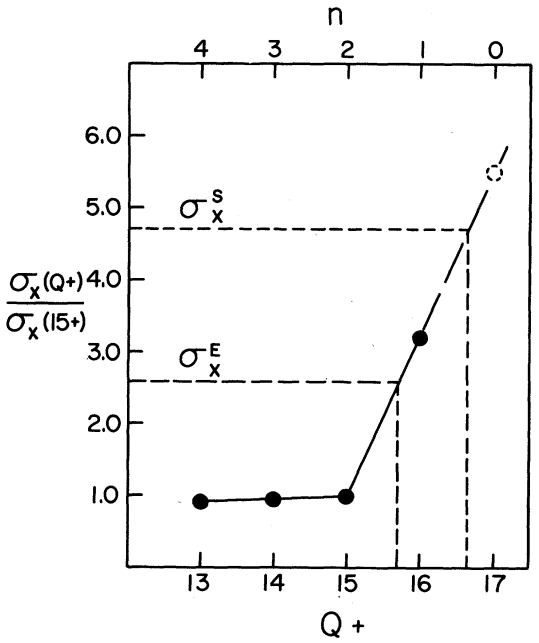

FIG. 1. Relative Cu K cross sections for $Cl^{13+-16+}$ and the σ_x^E and σ_x^S modes at 140 MeV.

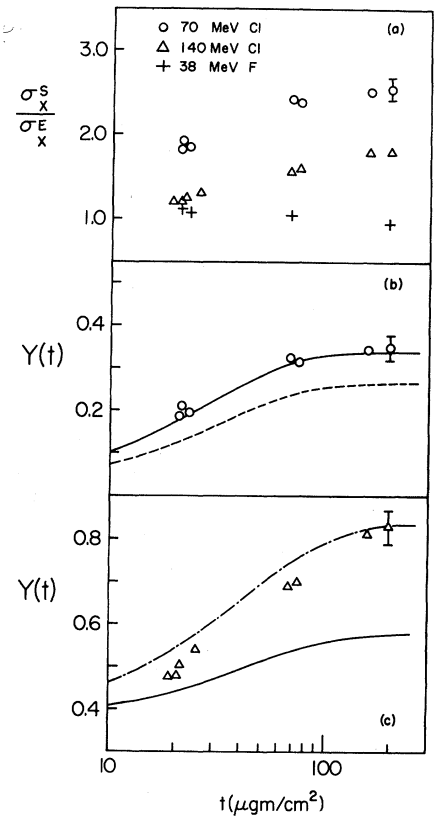

FIG. 2. (a) Ratios $R=\sigma_x^S/\sigma_x^E$ as a function of carbon thickness for Cl and F beams. (b) Experimental values and theoretical curves for Cl K-vacancy fraction $Y(t)$ at 70 MeV. (c) Experimental values and theoretical curves for Cl K-vacancy fraction $Y(t)$ at 140 MeV.

pected under actual single-collision conditions, with the increase due to charge exchange from the Cu K shell directly into the Cl K hole. Further the additional stepup for Cl^{17+} should be about the same, as represented by a dashed extension in the figure. Accordingly, the following analysis takes the contribution to the Cu K cross section due a fully vacant Cl K shell to be given by $\sigma_x^K=2(\sigma_x^{16+}-\sigma_x^{15+})$ and extends the 140-MeV results to the 70-MeV case, again with support from the Kr data. It should also be mentioned that the Cu K fluorescence yield is assumed to be constant, with relative x-ray yields being equivalent to relative vacancy cross sections.

The relative cross sections σ_x^E and σ_x^S at 140 MeV using an ~200-μg/cm^2 carbon backing are displayed in Fig. 1 as dashed lines. A 100-μg/cm^2 prefoil gave the same results. The yield for σ_x^E implies that the charge-state distribution emerging from the prefoil includes a significant percentage of ions with K vacancies, as might be expected at this energy. The remarkable aspect of Fig. 1 is that the quantity σ_x^S is substantially greater, a result which is here attributed to residual K-shell excitation in the Cl ions built up in the carbon which persists during the $<10^{-16}$-sec transit time through the Cu.

The ratios $R=\sigma_x^S/\sigma_x^E$ as a function of the carbon-backing thickness for 70- and 140-MeV Cl are shown in Fig. 2(a), along with a set for 38-MeV F. The F results are essentially unity, consistent with the slight dependence[6] of the Cu K cross section on the presence of F K vacancies. The ratios for Cl increase steadily to limiting values at $t_c\approx200$ μg/cm^2. Changes in σ_x^S due to energy loss in the carbon are estimated to be only a few percent for the thickest foils. As a rough test of the lifetimes of excited states involved at 70 MeV, the prefoil was placed approximately 1 mm from the Cu targets on the ~70-μg/cm^2 backings. The ratio R in this configuration was only ~5% lower, indicating that the vast majority of states with K vacancies decayed within 10^{-10} sec. The result also verified a theoretical conclusion that contributions to σ_x^S from recoiling carbon atoms are clearly negligible in the present experiment. The error bars in Fig. 2 all represent repeatability. Relative geometrical and integration errors should be less, with the

discrepancy attributed to problems with uniformity of the Cu and C layers.

By taking the excess of $\sigma_x{}^S$ beyond $\sigma_x{}^{15+}$ to be a direct reflection of vacancies in the Cl K shell, the values R have been converted into fractions of the beam exhibiting K-shell excitation (vacancies), $Y(t)=(\sigma_x{}^S-\sigma_x{}^{15+})/\sigma_x{}^K$, which are graphically presented in Figs. 2(b) and 2(c). Experimentally the cross sections $\sigma_x{}^{11+-15+}$ and $\sigma_x{}^E$ at 70 MeV were found to be within 10% of each other, indicating no appreciable fraction of Cl^{16+} or Cl^{17+} in the emerging beam.

Within a simple framework the rate equation and the concomitant expression for the fraction of states formed with K vacancies in ions penetrating a solid can be given as[4]

$$dY/dt=\sigma_v(1-Y)-(\sigma_c+\sigma_\tau)Y, \quad (1)$$

$$Y(t)=(\sigma_v/\sigma)[1-\exp(-\sigma t)]+A\exp(-\sigma t). \quad (2)$$

Here $Y(t)$ is the fraction as a function of distance t into the solid, σ_v is the cross section for creation of K vacancies, σ_c is the cross section for electron capture directly into the K shell, and $\sigma_\tau=(nv\tau)^{-1}$ is a "filling" cross section due to K transitions of lifetime τ within an ion moving at velocity v in a medium of density n. In Eq. (2), σ equals $\sigma_v+\sigma_c+\sigma_\tau$ and A is the initial fraction with K vacancies upon entering the solid.

It is necessary in the present situation to take the competing cross sections as average quantities, i.e., all states are treated as one. The quantity A has been measured here to be 0 and 0.35 for 70 and 140 MeV, respectively, where $A=(\sigma_x{}^E-\sigma_x{}^{15+})/\sigma_x{}^K$. A lifetime τ of 0.97×10^{-14} sec for Cl has been obtained by scaling the measured lifetime for S K transitions[4] by the factor $\tau_{Cl}{}^t/\tau_S{}^t$, where $\tau_{Cl}{}^t$ and $\tau_S{}^t$ are the theoretical values[7] for the singly ionized ions. Estimates for σ_v have been taken from two sources of data,[6,8] with the assumption that σ_v arises from ionization of the Cl K shell by the neutral carbon atoms. The quantities σ_c have been calculated from the Brinkman-Kramers expression given by Nikolaev[9] for charge exchange, normalized by the factor 0.1 as indicated by the Cl-Kr experiment. Table I contains the sets of values used. It is important to note that an accurate scaling of the Brinkman-Kramers theory is not critical here, since σ_c is almost negligible.

The curves generated from Eq. (2) with sets 1 and 2, appearing in Fig. 2(b) as solid and dashed lines, respectively, are both successful in simulating the 70-MeV data. The somewhat better agreement with set 1 is perhaps fortuitous in view of the several assumptions upon which the experimental and theoretical descriptions are based. For 140 MeV, set 3 produced the solid curve in Fig. 2(c), which reproduces the general trends but departs more noticeably from the data. At this energy there presumably are significant fractions of few-electron and thereby metastable states in the Cl distribution within the carbon. A hypothetical situation illustrates the dependence of the fraction curve upon the introduction of longer lifetimes. The dot-dashed curve in Fig. 2(c) was obtained by arbitrarily assuming that $\frac{2}{3}$ of the collisions within the solid produce metastable ($\tau\gtrsim10^{-13}$ sec) states and $\frac{1}{3}$ produce promptly decaying ($\tau\approx10^{-14}$ sec) states. A precise knowledge of those relative populations would be needed for a final comment, but the allowance for metastables is evidently an important consideration at the higher energy.

TABLE I. Rearrangement cross sections (in units of 10^{-19} cm^2).

	σ_v	σ_c	σ_τ
70 MeV			
Set 1	2.44[a]	0.09	4.16
Set 2	1.70[b]	0.09	4.61
140 MeV			
Set 3	4.60[a]	0.16	3.25

[a]Estimated from Ref. 6.
[b]Estimated from Ref. 8.

In summary, this Letter presents a quantitative measurement of the presence of K vacancies in Cl ions passing through carbon. For cases of ions with and without K vacancies initially, the K-vacancy fraction as a function of penetration depth is suitably described by a simple model of competing processes for rearrangement of the Cl K shell. Depending on the fluorescence yields for the ions emerging from the thicker foils at these energies, the loss of residual K excitation would increase average charge states on the order of ~0.5 at 70 MeV and ~0.8 at 140 MeV.

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Hyperfine Quantum Beats in Oriented ^{14}N IV†

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Quantum beats have been observed in both linear- and circular-polarized light using a beam–tilted-foil geometry for the $3s\,^3S$–$3p\,^3P$ transition of ^{14}N IV. Beats between the $F=0$ and $F=1$ hyperfine levels—forbidden in the case of excitation by untilted foils—were observed. A value of $A=695\pm15$ MHz was obtained for the hyperfine coupling constant of the upper term.

Much recent attention has been given to the measurement of quantum beats produced by atomic alignment in the beam-foil source, and its use in determining unresolved fine and hyperfine structures. The initial suggestion for such a technique was made by Macek[1] and his prediction was verified by Andrä[2] for ^{1}H I and ^{4}He I fine structure. More recently, extensive measurements have been carried out for the light atoms ($Z\leq4$).[3] Until now, however, all field-free modulations observed were due to differences in the excitation cross sections to different m_L states; no excitation coherence between different m_L states was necessary or observed. It has been suggested theoretically[4,5] and verified experimentally[6] that if the cylindrical symmetry of the beam-foil source is broken by tilting the foil, atomic orientation can occur leading to the emission of circularly or elliptically polarized light, demonstrating that excitation coherence between different m_L states is produced. In this paper, we demonstrate the feasibility of using this effect to measure hyperfine structure by the observation of quantum beats in circularly polarized light. The work of Ellis[4] showed that in a tilted-foil geometry such beats should occur. Of particular interest is the prediction that $J=0$ to $J=1$ (or $F=0$ to $F=1$) quantum beats which do not occur in linearly polarized or unpolarized light —and which are forbidden entirely for untilted foils—should be observable if circularly polarized light is detected. Hence the observation of $J=0$ to $J=1$ quantum beats can provide a sensitive measure of orientation in a time-resolved atomic excitation, and possibly allows the measurement of fine and hyperfine structure in cases where alignment is lacking. This Letter reports the first measurement of this phenomenon.

The Dynamitron accelerator at Argonne National Laboratory provided beams of a few microamperes of $^{14}N^+$ at 2.0 MeV which were excited by carbon foils mounted either perpendicular to the beam (0° tilt) or at 45° to the beam. The light emitted perpendicular to both the foil normal and