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Evidence for Radiative Electron Capture by Fast, Highly Stripped Heavy Ions*

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The first observations of unusually energetic x rays from fast heavy-ion collisions in which the projectile ion captures a free or weakly bound target electron are reported. Energy calculations based on this model of radiative electron capture are in reasonably good agreement with the observed x-ray data. The phenomenon has been observed for 10- to 140-MeV sulfur, chlorine, and bromine ions incident on various targets from boron to uranium.

Inner-shell vacancies created when fast heavy ions collide with target atoms can decay by the emission of characteristic x rays. High charge states which are reached at sufficiently large ion velocity impede this process since bound outer electrons may no longer be available to fill the inner-shell vacancy. X-ray spectra obtained under such conditions with beams of sulfur, chlorine, and bromine ions have revealed the existence of a new feature, a complex emission band, which occurs well above the highest characteristic x-ray line for the projectile. This newly observed phenomenon is attributed to radiative electron capture (REC) by the highly stripped ion. Specifically, the ion can capture a free or weakly bound target electron directly into a K-shell vacancy with the subsequent emission of an x-ray photon. The energy of the photon is given approximately by the sum of the binding energy of a K electron in a hydrogenlike or heliumlike ion and the kinetic energy of an electron which is at rest in the target, relative to the moving ion. The most probable photon energy is otherwise independent of the target material. It is well known that similar processes can occur for heavy ions in dilute hot plasmas which exist in the solar corona and in some x-ray stars, and which are attainable in fusion research laboratories.[1] In these cases, the electrons to be captured have a broad thermal velocity distribution which is mirrored by the broad, continuous electron-capture x-ray spectrum. In contrast, the process investigated here arises from a more sharply defined distribution, for example, the Fermi distribution of electrons in a metal; consequently, the spectral features are more distinct and reflect certain properties of the target material.

Beams of highly stripped sulfur, chlorine, and bromine ions with energies up to 140 MeV are produced by three-stage operation of the MP tandem Van de Graaff facility at Brookhaven National Laboratory. Thin (5 to 150 $\mu g/cm^2$) and thick targets of 25 different materials from boron to uranium are used to produce x rays. The detection system is a well-calibrated, high-resolution, 30-mm^2 Si(Li) detector system with pileup rejection. The system is sensitive to x rays in the range 0.8 to 60 keV. In addition, during the sulfur and some of the chlorine runs, the x-ray beam was filtered through polyethylene film (thickness 0.12, 0.24, and 0.36 mm). Since the resulting attenuation in the region of the REC lines is small, the major effect of the absorber is to reduce the counting rate in the region of the

sulfur and chlorine K lines to a level which leads to a greatly reduced pileup. Measurement of (i) the transmitted beam with a Faraday cup and (ii) the Rutherford scattering of the beam with two Si heavy-ion detectors placed at various angles establishes absolute cross sections for x-ray yields. Further details concerning the experimental and data analysis procedures are given elsewhere.[2]

Selected raw data are shown in Figs. 1(a)–1(g). They have not been corrected for the energy-dependent detector efficiency, silicon K escape peak, Doppler shift, absorber transmission, or residual pileup. Lines on each of the figures indicate the expected laboratory energy of the REC spectral feature for an electron which is at rest in the target.

Several generalizations are immediately evident from the full data: (1) A new spectral feature whose energy is in agreement with calculations based on the REC model indicated above is present; (2) in some cases the feature is sharp and in others it is broadened into a continuum [cf. carbon and nickel curves of Fig. 1(e)]; (3) in the case of the relatively sharp feature, the width of the line is still between 2 and 3 times wider than the instrumental resolution; (4) the cross section for REC seems to increase with increasing target atomic number. The last two effects are derived from the sulfur data where the counting statistics are better.

K-shell REC can occur with high probability only for fully or almost fully stripped ions. When outer-shell electrons are present, decays involving them are expected to dominate and K-shell vacancies will be short lived. Large numbers of highly stripped ions are, however, produced in swift ion-atom collisions. At 120 MeV, for example, the equilibrium charge distribution[3] of chlorine ions traversing a target is centered on $q=+14$. This implies that significant numbers of ions in charge state +15, +16, and +17 are produced, some with appropriate electron configurations for REC. Incidentally, one of the consequences of these high charge states is the large energy shift, ΔE, of the characteristic K x rays. Calculations based on these configurations agree with the observed shifts ($\Delta E \sim 150$ eV for sulfur $K\alpha$ at 120 MeV beam energy).

It is interesting to note that the cross sections for REC derived from the present data are in fair agreement with expectations based on calculations for the simple case of radiative capture of a free electron by a bare nucleus.[4] For example, for a 120-MeV sulfur nucleus the theoretical cross section is about 200 b/electron, whereas our preliminary experimental cross sections are ~500 b/target atom in carbon, ~1800 b/target atom in aluminum and magnesium, and $\sim 10^4$ b/target atom in nickel. In evaluating these experimental cross sections it has been assumed that approximately 20% of the beam particles are in charge states +15 or +16. The experimental data indicate clearly that some target materials can contribute more electrons per atom than others to the REC process.

There are two significant contributions to the observed width of the REC line. (I) The structure of the REC spectrum should reflect the distribution of ionic charge states. For example, the difference in binding energy of a K electron in S^{14+} and S^{15+} is about 250 eV. Therefore, capture of target electrons in the same initial state by each of these ions will produce x rays whose energies differ by 250 eV. (II) The density distribution of electrons in the target contributes to the spectrum. Consider, for example, a nickel target. The electrons obey a Fermi distribution up to the Fermi edge at about 5 eV. Neglecting small effective-mass contributions to the Brillouin zone boundary, this distribution transforms to the rest frame of a 120-MeV sulfur projectile as a broad symmetric distribution with a full width at half-maximum of about 300 eV. The combination of the effects of ionic charge state and electron energy distributions with an instrumental full width at half-maximum of about 250 eV in the region of interest can account qualitatively for the shape of the observed REC features. As the projectile energy is lowered, the width of the transformed distribution is narrowed and this effect is discernible in some of the data. No contribution to the linewidth is expected as a result of the very short collision times (about 10^{-18} to 10^{-19} sec) since the initial state is long lived and, hence, well defined in energy.

In another series of experiments, the L x rays produced in swift bromine ion collisions (up to 140 MeV) have been studied [Fig. 1(d)]. Spectral features appear on the high-energy side of the complicated Br L spectrum, and it is quite possible that REC to the bromine L shell is being observed. For example, the equilibrium charge state[3] of 140-MeV bromine ions is between +19 and +23, but there is a high probability of further ionization during those collisions which lead to the observed L x rays. As before, REC can become a possible decay mode only when few outer-

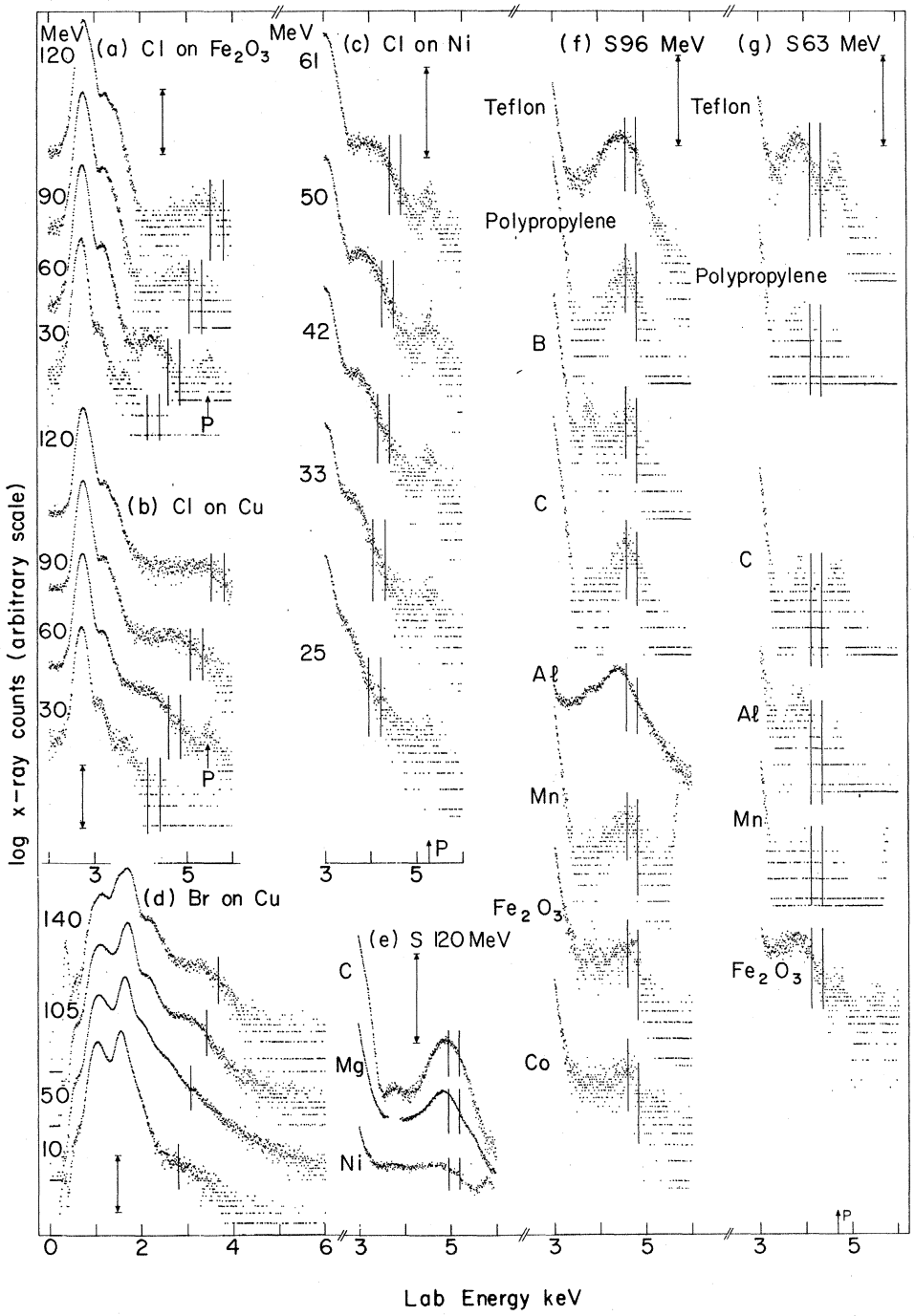

FIG. 1. Radiative electron capture x-ray spectra. The expected lab energy of REC spectral features, calculated for the cases of one and two initial K vacancies, and including the relevant Doppler shift, are indicated by short, solid, vertical lines. In some cases, the position of residual pileup is indicated on the energy scale by arrows labeled P. Target species and projectile energy in MeV are indicated near each curve. In (a) and (b) the intense peak is the chlorine $K \rightarrow L$ transition and is followed by a weaker $K \rightarrow M$ transition. The $K \rightarrow L$ transition is suppressed in (c). In (d) the first and second intense peaks are complexes of copper and bromine L lines, respectively. In (e) through (g) the sulfur K lines are suppressed. In some cases, additional weak peaks occur which may be due to target impurities [(e)–(g)]. Most of the targets had 5–10 $\mu g/cm^2$ backing of carbon and/or Formvar. In each set of figures one decade on the vertical scale is indicated by a double-ended arrow.

shell electrons are available to fill an inner hole, and this requires a charge state $q \gtrsim +26$. Thus, the existence of L-shell REC would tend to support the idea that close collisions often result in the removal of a large number of outer-shell electrons rather than several inner-shell electrons.

The agreement between predicted and observed values of the REC line positions is best at high projectile energy. At lower energies, the measured feature occurs at an energy somewhat lower than expected from our simple model. A significant correction may arise due to the noticeable degradation of beam energy in thick targets. Better understanding of position, width, and production cross sections of REC features requires the development of more sophisticated theoretical models.

Further experimental work is in progress to establish the angular distribution and polarization of the REC radiation. Gaseous targets will also be investigated to determine how the capture process is changed when the target electrons are distributed in sharply defined states of widely differing energy. Results from these experiments will test specific predictions of the present model.

Provided that the model is thoroughly established, REC can become an important diagnostic process in the interpretation of data from such diverse fields as astrophysics and solid-state physics. In addition, when the bromine data presented here are considered, it is clear that the REC process must also be included in the general discussion of x-ray spectra from heavy-ion collisions. REC lines could easily be blended with spectral features attributed to other processes, for example, combined atom effects, fusion products, and trace impurities in the beam or target.

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K-Shell Fluorescence Yield for Metallic Lithium and Other Light Elements*

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The K-shell fluorescence yield ω_K for metallic lithium was determined from intensity measurements of the K emission band excited in fluorescence with the synchrotron radiation of the 7.5-GeV DESY electron synchrotron. The value obtained for lithium is $\omega_K = (1.06 \pm 0.53) \times 10^{-4}$. Recently determined values of ω_K for Be, B, and C are tabulated. The value of ω_K for C previously published by the author was incorrect; the corrected value is $\omega_K = (13.0 \pm 3.9) \times 10^{-4}$.

The fluorescence yield of lithium has not yet been measured, although this element is deserving of special attention. A free lithium atom from which a K-shell electron is removed cannot show an Auger effect and therefore the fluorescence yield should be 1. However, following a K-shell ionization in solid lithium or the transfer of a K-shell electron of a free lithium atom to a high bound state, an Auger effect is possible and the fluorescence yield should be less than 1. This would mean that the fluorescence yield depends upon the configuration of the atom and the character of the chemical binding. Such conclusions are supported by the results of recent measurements on carbon by Toburen.[1] We have measured the fluorescence yield of metallic lithium and