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Coincident emission of a characteristic and a continuum x ray in electron-atom collisions

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An observation of the simultaneous emission of a characteristic *K* x ray and a continuum photon has been made for 70-keV electrons bombarding target atoms of Fe, Cu, Y, and Ag. The absolute cross section for Y and Ag agree well with a model that considers a contribution from both double-bremsstrahlung and electron-electron bremsstrahlung processes. The data for Fe and Cu, on the other hand, are about an order of magnitude higher than the model, suggesting the possibility of a resonant polarization bremsstrahlung contribution to the double-bremsstrahlung process.

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Since the earliest observation of the x-ray spectrum, it has been customary to consider the continuum or bremsstrahlung part of the spectrum to arise from the radiation of the electron scattered in the Coulomb potential of the atomic field. The characteristic x ray, on the other hand, is considered to arise from the distinct and independent process of inner-shell ionization (or possibly excitation) followed by the emission of the x ray as an electron from an outer shell of the atom makes a transition to fill the inner-shell vacancy.

Here we report a measurement of the cross section for the simultaneous emission of a *K* x ray and a bremsstrahlung photon in the bombardment of 70-keV electrons on atoms of Fe, Cu, Y, or Ag. The photons are detected at ±45° to the direction of the incident electron beam. One photon is within a narrow energy window (a few keV) centered on the characteristic *K* x ray of the target atom and the second photon is in an energy window from 15 to 25 keV. The two photons are detected within a time resolution of about 50 ns.

There are several processes that may be considered to lead to the simultaneous emission of a characteristic x ray and a bremstrahlung photon. First, there is the process of double bremsstrahlung (DB), where one of the two bremsstrahlung photons happens to have the energy of the characteristic x ray, within the resolution of the detector. The experimental detection of DB was reported by Altman and Quarles in 1985 for 75-keV electrons on target atoms of Ag, Tb, Au, and U [1]. Recently, Hippler [2] has reported DB measurements for 8.8- to 12-keV electrons on Ar, Kr, and Xe; and Kahler, Liu and Quarles [3] have reported measurements for 70-keV electrons on target atoms of Al, Cu, Ag, Tb, and U. There are two available theoretical models for the DB process. The cross section was calculated in 1977 in the relativistic first Born approximation by Smirnov [4]. The formula of Smirnov has recently been checked by direct numerical calculation [5]. The Smirnov formula has been integrated over the unobserved scattered electron to obtain cross-section predictions for comparison with experiment [1,3]. A nonrelativistic Coulomb approximation for DB has been used by Veniard, Maquet, and Gavrila [6] and independently by Florescu and Djamo [7]. The results of Refs. [1] and [2] are significantly higher than either theory. However, the results of Ref. [3] are in fair order-of-magnitude agreement with theory and exhibit a *Z* dependence that is suggested by the nonrelativistic Coulomb calculations [8].

Whereas DB originates from an electron which radiates in the Coulomb field of an atomic nucleus, a second form of bremsstrahlung which can occur when electrons are incident upon an atom is the process of electron-electron bremsstrahlung (EEB). In general, EEB occurs whenever an incident electron is accelerated in the field of a second electron. This second electron may be free or may be bound to an atom. In the case of bound electrons, EEB would be produced by an ejected electron radiating in the field of the scattered electron, or vice versa. The only direct measurement of this process has been reported by Komma and Nakel [9] in a coincidence experiment for 300-keV electrons on a range of target atoms. In this experiment, the contribution from the triply differential cross section for EEB, for normal bremsstrahlung and the doubly differential cross section for *K* shell ionization were separated kinematically. A counterpart to EEB from bound electrons exists in the framework of heavy-particle collisions, in which a target-atom electron is scattered by the Coulomb field of the incident projectile and radiates a bremsstrahlung photon. This process has been referred to as radiative ionization (RI) since the final state is one in which the atom is ionized. RI has been calculated by Ishii and Morita [10] and found to make a significant contribution to the single photon x-ray spectrum observed for C and Al targets bombarded by protons of energy of a few MeV. For the case of incident electrons, the EEB process for bound electrons will also produce ionization of the atom. The vacancy created may thus result in the coherent emission of a characteristic x ray in coincidence with the bremsstrahlung photon. This being the case, one might expect to see an enhancement of the DB process over a continuum of x rays detected in coincidence with a characteristic x ray. This process may of course occur for any bound electron; however, the present work focuses only on the case in which a vacancy is created in the *K* shell. Hence, in the context of the present work, RI may be defined as the process in which a characteristic *K*-shell x ray is emitted in coincidence with a continuum x-ray produced by EEB. Alternatively, the continuum radiation part of the process could be described as Compton scattering by the inner-shell electron of a virtual photon radiated by the incident electron. In contrast to DB, RI would be a two-step process in which the emission of the K x-ray is considered to occur after the initial interaction has occurred. The emitted x ray is expected to be isotropic or uncorrelated in angle with either the incident electron direction or the radiated continuum photon. Thus the contribution from RI may be predicted by taking the EEB cross section multiplied by the fluorescence yield divided by 4π. The EEB cross section has been calculated by Haug [11] for EEB from a free (very loosely bound) electron. Calculations of EEB for bound inner-shell electrons have been done by Haug and Keppler [12] for the case studied in Ref. [9], but calculations are not available for the present experimental conditions.

Finally, there is the process of atomic or polarization bremsstrahlung (PB) which was proposed by Amusia in 1982 [13]; and has been recently reviewed by him [14]. In this process, a photon is radiated by the atom as it is polarized by the passage of the incident charge. Although Hippler [2] has suggested this effect as a possible explanation for the discrepancy observed in the DB measurements, the theory of DB to date has not taken the possibility of a PB contribution into account. That is, the two photons radiated in DB are assumed to originate from the incident or scattered electron. In addition, one should consider that one or both of the radiated photons could originate from the atom, or from the bound atomic-electron cloud as it is polarized, rather than from the free electron. While this PB component in DB has not been calculated, it has been suggested that in single bremsstrahlung, this process may be much larger than the usual bremsstrahlung from the electron, especially when the photon energy is near one of the transition energies of the target atom [14,15]. It is reasonable to assume that there would also be some resonant enhancement in the case of DB, especially when one of the radiated photons is near one of the characteristic x rays of the target.

The first effort to study this two-photon emission process utilized the electrons from a ^{147}Pm β decay source to bombard targets of Fe, Zn, Se, Y, Mo, Ag, and Sn of various thicknesses. Preliminary results using targets of about 5 mg/cm^2 have been reported. However, these preliminary results, unlike those of the present experiment, have a significant contribution from the additional incoherent process in which the incident electron may ionize the K shell of one target atom producing a second electron and a K x ray, and then either electron may radiate a coincident bremsstrahlung photon in the Coulomb field of a second target atom.

The experimental coincidence setup has been described in detail previously [3,16]. Incident electrons of 70 keV are provided by an electron accelerator. Targets are positioned normal to the incident beam within a small aluminum scattering chamber which serves as a Faraday cup for charge collection. The targets used are thin films of Fe, Cu, Y, and Ag of approximately 50 μg/cm^2 thickness, which is thin enough in each case to ensure single collision conditions and renders correction for photon attenuation and electron energy loss in the target negligible. All of the targets have a 15 μg/cm^2 carbon backing and the thicknesses are known to roughly 10%. The intensity of the electron beam is monitored by a current integrator and is held at typically 0.1 nanoamps. Photons are detected at ±45° to the incident beam in two collimated and planar Hp-Ge detectors which are shielded from each other. This geometry was chosen to optimize the solid angles and to eliminate crosstalk between the detectors. Individual events consist of the delay time Δt between the two detected photons and their respective energies k_1 and k_2. Software was developed for processing the data to obtain a two-dimensional energy array of the net coincidence probability with the statistical error. To do this, the total events from a run are sorted to produce two energy arrays corresponding to events whose delay times fall inside and outside of the real coincidence timing peak region. A net coincidence energy array is computed by subtraction of the two energy arrays, appropriately normalized.

Energy calibration and testing of the coincidence system has been previously described [3]. Briefly, two techniques were used. First, a calibrated ^{133}Ba radioactive source was used to provide an energy calibration and to determine solid angles; and, second, the $K\alpha$-L coincidence cascade from the single K-shell ionization of terbium was used to test the accuracy of the system. An *in situ* measurement of the $K\alpha$-L cascade of Tb (in a separate experiment using a 50 μg/cm^2 TbF$_3$ target) provides an excellent means of both calibrating and testing the system. The advantage is that the $K\alpha$-L data is taken under identical experimental conditions as the experimental data, providing an absolute scale for the measured cross sections and reducing the major uncertainty to a statistical one. To test the system, the cross section has been determined for the $K\alpha$-L coincidence. For the present setup, a result of 5.6 ± 1.1 mb was obtained which agrees well with the theoretical value of 5.5 ± 0.8 mb. The theoretical value was calculated from

$$\frac{d\sigma_{KL}}{d\Omega_1 d\Omega_2}=\sigma_K\frac{\omega_K\omega_L}{(4\pi)^2}\frac{P(K\alpha)}{P(K\alpha)+P(K\beta)}, \tag{1}$$

where σ_K is the cross section for producing a K-shell vacancy, $P(K\alpha)$ is the probability that the K shell will decay by a radiative transition specifically from the L shell, and $P(K\beta)$ is the probability that the K shell will decay by a radiative transition specifically from the M shell. ω_K and ω_L are the K and L shell fluorescence yields, respectively. Fluorescence yields were obtained from Ref. [17], $P(K\alpha)$ and $P(K\beta)$ were obtained from Ref. [18], and σ_K was obtained from Ref. [19].

The differential cross section for the two-photon emission process can be determined from

$$\frac{d_4\sigma}{dk_1\,dk_2\,d\Omega_1\,d\Omega_2}=\frac{N_c}{N_0 t\,\Delta k_1\Delta\Omega_1\varepsilon_1(k_1)\Delta k_2\Delta\Omega_2\varepsilon_2(k_2)} \tag{2}$$

where N_c is the number of coincidences, N_0 is the number of incident electrons, t is the target thickness, $\Delta k_{1,2}$ are the detector energy windows, $\Delta\Omega_{1,2}$ are the detector solid angles, and $\varepsilon_{1,2}$ are the energy-dependent detector efficiencies. The product $\Delta\Omega_1\Delta\Omega_2$ is determined using a measured coincidence rate from the ^{133}Ba source. Δk_1

and Δk_2 are selected to define an energy window $\Delta k_1 \Delta k_2$ from which a two-photon rate is obtained for determining the absolute cross section. Detector efficiencies have been determined in a separate experiment.

The results are summarized in Fig. 1 for the cross section in units of b/sr^{2}keV versus atomic number. We have plotted the cross section evaluated from Eq. (2) multiplied by Δk_1 for that point. This produces an experimental cross section which is independent of the width of the window around the K x ray, the case expected if the cross section were dominated by the RI process. Each data point gives the result for an energy window of width $\Delta k_2 = 15$–25 keV centered at the average value of $\langle k_2 \rangle = 20$ keV. The photon energy window was chosen to obtain acceptable statistical errors, and is a reasonable selection since the theory does not vary significantly over this range. The error bars represent the one standard deviation statistical error in the net number of coincidences. As was the case for the DB measurements reported previously [3], the systematic errors in target thickness, charge collection, solid angle, and detector efficiency are small compared to the statistical error, and subtraction of a target-out background was found not to be necessary.

The theoretical predictions are shown as lines. The dash-dotted line is the DB prediction from our numerical integration of the relativistic first Born approximation of Ref. [4] for 70-keV incident electrons and photon emission angles of 45°, multiplied by the energy width of the K x-ray peak, Δk_1. Typically, Δk_1 was around 2 keV for the data shown. The dashed line gives the RI prediction of our evaluation of the EEB formula of Haug [11] for 70-keV electrons and a photon emission angle of 45°. The EEB cross section has been multiplied by the K-shell fluorescence yield [16] to account for the radiation of the K x ray, and is divided by 4π since the x ray is assumed to be emitted isotropically. The solid line is the sum of the two theoretical models.

The experimental results for Fe and Cu disagree with the sum of the theories by factors of about 18 and 13, respectively. The results for Y and Ag, however, are in good agreement, although each has a sizable statistical error. Thus the data support the suggestion of a resonant enhancement of the DB rate for Fe and Cu when the incident electron energy is 70 keV. There are not yet any calculations for the PB effect for the conditions of the present experiment. However, calculations of PB for single photon emission are consistent with such an enhancement for certain energies and target atoms [14,15].

In Fig. 2, we present the data from the current experiment along with the data for double bremsstrahlung from Ref. [3] plotted versus photon k_1 for k_2 in a 10-keV window centered at 20 keV. The cross section is plotted in this case, as is appropriate if the data are to be interpreted as due primarily to the double-bremsstrahlung process. For the current data, the calculated contribution from the RI process has been subtracted from the data to exhibit only the expected double-bremsstrahlung effect. The data points at 20 keV for different Z's indicated are from Ref. [3] and show the Z dependence discussed there. The present data points for Ag and Y are seen to be in good agreement with the data of Ref. [3] and with the theoretical curves shown for the relativistic Born approximation. The dashed curve is our evaluation of the calculation of Ref. [4]; the solid curve includes the Elwert factor which has been useful in correcting the Born approximation in the case of single bremsstrahlung [20]. In contrast with the Ag and Y data, the data points for Fe and Cu are over an order of magnitude higher than the theory. The case for Cu is interesting here since the Cu point at $k_1 = 20$ keV is in good agreement with the theory whereas the point for k_1 equal to the Cu K x-ray is much higher than the theory. This suggests that there is an additional contribution from some other effect such as PB for the case of

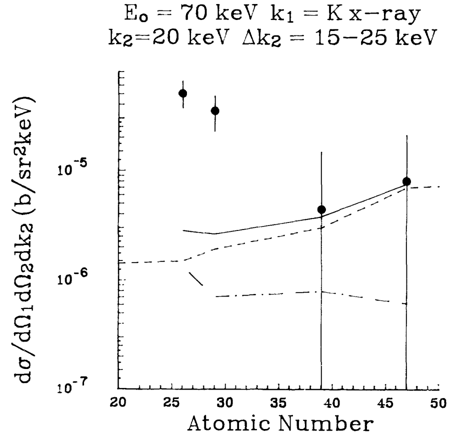

FIG. 1. Plot of $d\sigma/d\Omega_1 d\Omega_2 dk_2$ in b/sr^{2}keV vs atomic number. The incident electron energy is 70 keV, one photon, k_1, is the K x ray, the second photon is centered at 20 keV within a 10-keV window. The dash-dotted curve is computed from the formula of Ref. [4], integrated over the unobserved scattered electron and multiplied by Δk_1. The dashed curve is the cross section for free electron-electron bremsstrahlung of Ref. [11], multiplied by the K x-ray fluorescence yield divided by 4π. The solid curve is the sum of the two other curves.

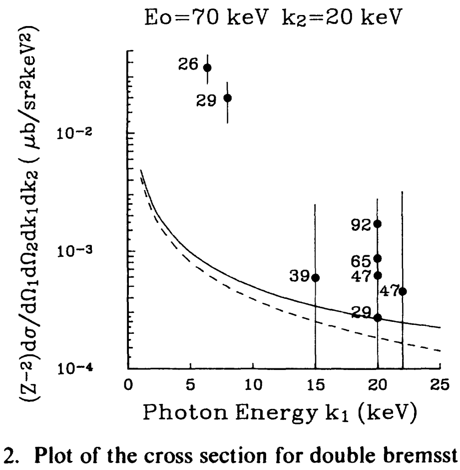

FIG. 2. Plot of the cross section for double bremsstrahlung in μb/sr^{2}keV^2 scaled by Z^{-2} vs the energy of photon k_1. The dashed curve is an integration of the formula of Ref. [4] over the unobserved scattered electron. The solid curve includes the Elwert factor. The appropriate atomic number is indicated for each data point.

Fe and Cu.

Since the transit time of the target by the electron is of the order of 10^{-15} sec it is not possible in the present experiment with 50-ns timing resolution to decide whether the two photon emission is a single step or two-step process on the basis of timing alone. However, with additional angular correlation measurements it may be possible to resolve this question. In a single step process, both photons are emitted simultaneously and the process would be dominated by DB or PB where one of the photons happens to have the energy of or near to the K x ray of the target. In this process the two photons are expected to be angularly correlated. In a two-step process, the RI mechanism is expected to dominate. The radiation of the continuum photon occurs in the electron-atom ionization. The K x ray is then emitted later (of the order of 10^{-15} sec) as the ion rearranges, and is not expected to be angularly correlated with the continuum photon.

In conclusion, we have presented a measurement of the absolute cross section for the coincident emission of a K x ray and a bremsstrahlung photon. The data for Y and Ag are in good agreement with a model which includes double bremsstrahlung and radiative ionization. The data for the lower-Z targets of Fe and Cu, however, are an order of magnitude higher than this model and suggest that there is a resonant enhancement in the coincidence rate that may arise from an atomic or polarization bremsstrahlung contribution to the usual two-photon bremsstrahlung process.

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