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RADIATIVE CAPTURE AND BREMSSTRAHLUNG OF BOUND ELECTRONS INDUCED BY HEAVY IONS*

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Abstract:

X-rays emitted during the radiative capture of target electrons into the K-shell of fast and highly stripped projectiles were observed. When using targets with strongly bound electrons, a high-energy x-ray tail was also found; this new process is a type of electron bremsstrahlung. The cross sections for both these processes can be explained quantitatively.

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In the x-ray emission accompanying the passage of fast highly stripped heavy ions through gases, we could distinguish three types of beam associated radiation.

1. Characteristic x-rays emitted following electron transfer into the L-, M- and outer shells of a stripped ion.

2. A broad x-ray band from the radiative capture of bound electrons from the target into the K-shell of the fast projectile. The energies correspond to the difference of the electron binding energies in the initial and final state plus the electron kinetic energy relative to the projectile and reflect the momentum distribution of the bound electrons. This radiation has been recently identified by Schnopper, et al.[1]

3. A high-energy tail going up to an energy corresponding roughly to $\hbar v/a$ where v is the projectile velocity and a is equal to the Bohr radius. This new process we ascribe to bremsstrahlung from bound target electrons in the Coulomb field of the projectile.

The x-ray emission was studied when high energy ^{40}Ar, ^{20}Ne, and ^{14}N beams passed through targets of gaseous molecules and simple noble gases up to argon. Beams of ^{40}Ar were obtained from the L.B.L. SuperHILAC at energies up to 7.21 MeV per nucleon (MeV/n) and then stripped in the 6 μm Al entrance window of the gas target cell to an equilibrium average state of about 17^+. The ^{20}Ne and ^{14}N were accelerated in the L.B.L. 88"-Cyclotron to 7.0 MeV/n and 11.42, 17.86 MeV/n respectively, and were essentially completely stripped upon entering the gas target. The x-ray-spectrometers were a 5 mm dia., thick Si detector and a 1 cm dia., thick Ge detector coupled to low-noise pulsed-light feed-back amplifiers with a peaking time of 9.5 μs and a fast pile-up rejector. The energy resolution measured with Fe K_α x-rays was 165 eV and 240 eV f.w.h.m. for the Si and Ge detectors, respectively. The instantaneous count rates were kept below 3000/s to avoid spectral distortions due to pile up. The x-rays at 90° to the beam were collimated to an angular divergence of less than 0.1 radians to keep the Doppler broadening of the x-rays emitted by the fast ions smaller than the detector resolution. Using a ^{57}Co standard source, we could determine the detection efficiency at 6.4 and 14.4 keV absolutely. The background produced by the beam passing through the evacuated chamber was measured to be negligible in all cases.

Figure 1 shows sample x-ray spectra from the He and Ne gas targets. Besides the K-rays in the Ar run, which have energies expected for transitions in

Ar(16$^+$),one sees broad lines. They are beam associated, because their peak energies change only with the energy and the species of the projectile, but not appreciably with the target atom. In agreement with Ref. 1 we assign these broad x-ray lines to radiative capture of bound electrons from He or Ne into (mainly) K-orbits of the highly stripped projectiles. If one considers the electrons quasifree, with an intrinsic momentum $\vec{p}_i$ in a potential U_i, moving with a momentum $\vec{k}$ towards the projectile considered at rest, one can intuitively derive the radiation frequency ω when the electron is captured in an orbit with a binding energy E_f:

$$\frac{(\vec{p}_i+\vec{k})^2}{2m_e} + U_i = \hbar\omega + E_f \quad \text{or} \quad \hbar\omega = (E_i-E_f) + \frac{k^2}{2m_e} + \frac{\vec{k}.\vec{p}_i}{m_e} \qquad (1)$$

This energy for the capture maximum is in fair agreement with the experimental results.

In addition, in the spectra of all targets with Z>6 we observed high-energy tails, such as those shown in Fig. 1. These radiation tails must have a different origin because their intensity relative to the capture spectrum increases with larger beam velocities. With 17.8 MeV/n ^{14}N, they dominate the spectra. We assign this radiation component to bremsstrahlung from strongly bound electrons. The cross section for bremsstrahlung radiated by an electron during a collision with a heavy particle of charge Z and velocity v is classically given by^2 (we use atomic units)

$$\frac{d^2\sigma_B}{d\Omega d\omega} \approx \frac{2}{c\pi\omega}\left(\frac{Z\ \sin\theta}{cv}\right)^2 \ell n \left(\frac{\rho\ \max}{\rho\ \min}\right) \qquad (2)$$

For a given frequency ω one has $\rho_{max} \approx v/\omega$ because for impact parameters larger than ρ_{max} the collision time $\tau \approx \rho/v$ is too long to produce significant radiation at that frequency. For bound electrons the quantum limit on the impact parameter is the limit down to which the electron can be localized. The upper limit to the bremsstrahlung spectrum $\omega_{max} \approx v/\rho_{min} \approx v/a$ increases with decreasing orbital radius a. Thus, strongly bound 1s electrons lead to high-frequency bremsstrahlung and we write $\omega_{max} = \lambda v \langle 1/r \rangle_{1s}$, where λ is a factor of the order of unity.

Loosely bound electrons, however, contribute mainly to the production of high energetic x-rays via radiative capture into inner atomic shells of the projectile, as mentioned in the paragraph before the last. The radiative capture of completely free electrons is treated by Bethe and Salpeter.[3] Bound target electrons are characterized by their Fermi motion i.e. by a distribution of velocities. If the velocity of the projectile is high compared to the orbital velocity of the target electrons, one can use unperturbed wave functions for the electron in target and projectile. We calculate the cross section for radiative capture within the impact parameter method.[4] For hydrogen-like wave functions, the result is

$$\frac{d^2\sigma}{d\Omega d\omega} = N_i N_f \frac{256\omega \sin^2\theta}{(\pi v)^2 c^3} \int d^3p \frac{\kappa_i^5 \kappa_f^5 (k + p_z)^2}{\left((\vec{p} + \vec{k})^2 + \kappa_f^2\right)^4 \left(p^2 + \kappa_i^2\right)^4} \times \delta\left((\omega - k^2/2 - E_i + E_f - p_z k)/k\right) \qquad (3)$$

N_i and N_f stand for the number of electrons in the target shell with principal quantum number n_i and for the number of available electron states in the projectile shell with principal quantum number n_f. The momenta κ_i and κ_f depend on the screened nuclear charges Z_{sc} through $\kappa = Z_{sc}/n$. The δ-function contains the dispersion relation of Eq. (1). In the region where the cross section is peaked ($p_z \approx 0$) the term $(\vec{p} + \vec{k})^2 + \kappa_f^2$ varies slowly and can be taken out of the integral. The cross section then factorizes into two parts: one, which contains the properties of the projectile and the other which gives information on the target. The latter enters in the form of its Compton profile[5], and it thus reflects the momentum distribution of the electrons in the target.

The theoretical curves for the He targets were calculated from Eq. (3) and then folded with the energy resolution of the detectors. For neon targets, because the inner electrons are so strongly bound that their upper bremsstrahlung energy exceeds the energy freed in the radiative K-shell capture of outer electrons, we added the cross sections for capture and bremsstrahlung. Equation (2) is only qualitative, and agreement with experiment is achieved if we weight the cross section for bremsstrahlung by a factor of 8 in the case of Ne on Ne and by a factor of 10 in the case of Ar on Ne. The corresponding values of λ are 2 and 3.5. We determined κ_i and κ_f from screened nuclear charges following Slater's[6] prescription. At the maximum of the K-shell capture peak the calculated cross sections in b/(sr keV) are found to be 24 for 7.0 MeV/n, Ne(10^+) on He, and 53 for 7.21 MeV/n Ar (17^+) on He. The experimental numbers are 24 and 50, respectively. For Ne as target the theoretical values are 73 (Ne(10^+)) and 155 (Ar(17^+)) compared to the experimental numbers 32 and 56. This discrepancy vanishes if one assumes a lower average charge of the projectiles in case of the Ne target. The assumption is reasonable because the radiationless electron capture (which we do not consider here) increases rapidly with the nuclear charge of the target. The number 73 is reduced to 41 if one uses Ne(9^+) instead of Ne(10^+). Note that both Ne(8^+) and Ar(16^+) do not contribute to the radiative capture into the K-shell.

To compare the experimental and theoretical shapes we have normalized the cross sections to equal height at their maximum. The binding energies $-E_i$ are taken from experiment and the binding energies $-E_f$ in the highly ionized projectile are calculated with Slater's method. Equation (3) predicts maximal intensity at an energy slightly higher than that observed in experiment; in the figures we shifted the theoretical maximum down to the observed one. The shifts were 300 eV for Ne(10+) on He and Ne(9+) on Ne, 50 eV for Ar on He, and 400 eV for Ar on Ne. They are probably due to screening effects. (In this paper we also did not consider relativistic corrections which are of the order $(v/c)^2 \approx 1.5\%$.) In all calculations we considered contributions of the target electrons to states in the projectile with main quantum numbers $n \leqslant 5$. This is sufficient because their contributions drop as $1/n^3$.

To summarize, we have found that with high-energy, heavy-ion projectiles a new radiation process (bremsstrahlung) occurs, and that with somewhat lower-energy projectiles we have confirmed the process of radiative capture. The position of the associated peak in the x-ray spectrum follows from energy consideration and its width is due to the Fermi motion of the bound target electrons. In addition, the cross section for these high-energy x-rays (those above the normal target or projectile x-rays) can be understood quantitatively. For the highest projectile velocities, this spectrum is dominated by the bremsstrahlung process because its cross section drops more slowly with increasing energy than that for radiative capture. For somewhat lower velocities the spectrum is dominated by direct capture of electrons into (mainly) the K-shell of the projectiles. At still lower projectile velocities (which we did not study), the formation of quasi-molecular states will influence the x-ray cross section.

FOOTNOTES AND REFERENCES

[*] Work performed under the auspices of the U.S. Atomic Energy Commission.

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FIGURE CAPTION

Fig. 1. Cross sections for x-rays at $\theta = 90°$ in collisions between fast ions and simple gases. The experimental results are shown as points, and the solid curve is the theoretical shape. On the low-energy side of the peaks, corrections for absorption of the x-rays in the windows and in the air-path between the chamber and detector become important. For the topmost curve, Ar on Ne, there was an additional 0.012 mm Al absorber. On all plots the ordinate scale goes with the high-energy peak. The greater importance of bremsstrahlung compared with radiative capture in the Ne targets is apparent in the plots for Ar and Ne projectiles. At high energies, as shown in the N projectiles, the ratio of bremsstrahlung to radiative capture is large even with the He target.

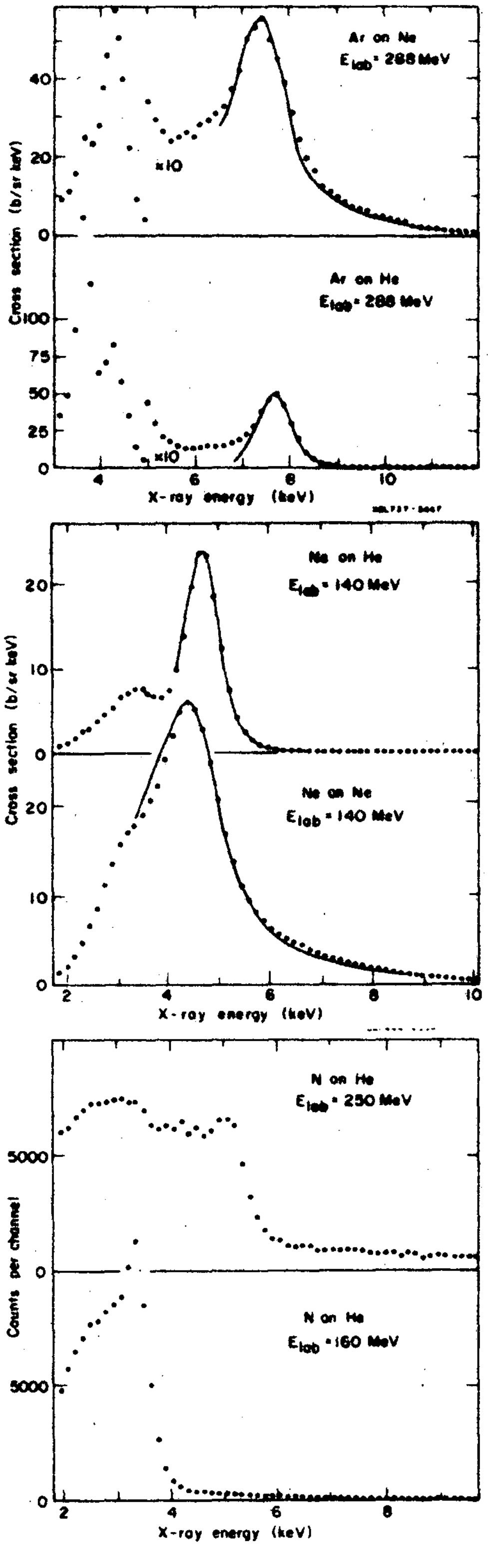

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Fig. 1

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