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Radiative Ionization in Slow Ion-Atom Collisions*

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ABSTRACT

Bremsstrahlung from the ionization of inner shell electrons in slow ion atom collisions is considered. The yield predicted by the binary encounter approximation is small compared with experiment in 12-33 MeV O + Zr and O + Au collisions.

In the Binary Encounter (BEA) theory[1] of electronic excitation in slow ion-atom collisions, electrons scatter from the projectile and are ejected from the atom. The consequences of this are two-fold: (1) vacancies are created and (2) the accelerated electron can radiate, producing a form of bremsstrahlung. We call this Radiative Ionization (RI) and it is analogous to inner bremsstrahlung in β^- decay[2] and the internal Compton effect in γ-ray internal conversion decay.[3] This process differs from secondary electron bremsstrahlung[4] in which ejected electrons collide with other target nuclei in a two collision process. In this process, electrons radiate while they are being accelerated in the primary ion-atom collision.

Jakubassa and Kleber[5] have previously considered this process, but their theory requires that the projectile velocity v_1 be much greater than the orbital velocity of the tightest bound electron v_K. Also using this high energy approximation, other groups have formulated similar treatments of this effect calling it Primary Bremsstrahlung[6] and Radiative Capture to the Continuum.[7] Our interest in this process arose from the observation of anomalous continua in 12-33 MeV O + Zr and O + Au collisions.[8] The ion velocity is comparatively small in these systems and the previously developed theories are inadequate. In this letter we shall attempt to reformulate the theory of RI to provide a better estimate for cases where $v_1 \ll v_K$.

If we have a cross section $d\sigma(\vec{v}_1,\vec{v}_2,\vec{v}_2')$ for a projectile of velocity $\vec{v}_1$ colliding with an electron of velocity $\vec{v}_2$ scattering it to $\vec{v}_2'$, the accompanying bremsstrahlung[2] is:

$$\frac{d^2\sigma}{dE_x} = \frac{2\alpha}{3\pi}\,\frac{|\vec{\Delta}\beta|^2}{E_x}\,d\sigma(\vec{v}_1,\vec{v}_2,\vec{v}_2') \qquad (1)$$

where $c^2|\vec{\Delta}\beta|^2 = |\vec{v} - \vec{v}'|^2$, $\vec{v}$ and $\vec{v}'$ are the relative velocities between the projectile and electron before and after the collision, E_x is the x ray energy, and α is the fine structure constant. This simple bremsstrahlung formula should hold approximately if $\omega\tau<1$ where $\hbar\omega = E_x$ and τ is the collision time between the electron and the projectile. Using the minimum collision time for τ, we can write:

$$\omega\tau \approx \frac{\omega Z_1 e^2}{E_2 v_2} = \frac{E_x}{E_2} \frac{Z_1 v_o}{v_2} = \left(\frac{E_x}{U_K}\right)\left(\frac{U_K}{E_2}\right)^{3/2} \frac{Z_1}{Z_2} . \qquad (2)$$

where $v_o = e^2/\hbar$ and E_2 is the initial kinetic energy of the electron. Although $E_x > U_K$, the condition $\omega\tau < 1$ is generally satisfied. For the large energy transfer needed to both ionize an electron and have it give up part of its kinetic energy to bremsstrahlung, E_2 must be much greater than U_K. Also, we will generally apply these formulas to systems where $Z_1 < Z_2$.

Following Gerjouy,[9] Eq. (1) is integrated using the Rutherford formula for $d\sigma(\vec{v}_1,\vec{v}_2,\vec{v}_2')$. The resulting cross section is:

$$\frac{d^2\sigma}{d\Delta E dE_x} = \frac{4\alpha}{3\pi} \frac{Z_1^2 e^4}{E_x \Delta E \mu v_1^2 \mu v_2^2} \times \begin{cases} \frac{v_2}{c} \left(\frac{v_1+v_2 - v_2'+v_1'}{c}\right) & b \leq \Delta E \leq a \\ \frac{2v_2^2}{c^2} & 0 \leq \Delta E \leq b \\ 0 & \text{Otherwise} \end{cases} \qquad (3)$$

where $v_2' = (v_2^2 + \frac{2\Delta E}{m})^{1/2}$, $v_1' = (v_1^2 - \frac{2\Delta E}{A_1 M})^{1/2}$,

$$a \text{ or } b = \frac{4A_1 Mm}{(A_1 M + m)^2} (E_1 - E_2 \pm \tfrac{1}{2}(A_1 M - m) v_1 v_2) \quad \text{respectively,}$$

ΔE is the energy transferred to the electron $= \frac{1}{2} m(v_2'^2 - v_2^2)$, and A_1M, m, and μ are the mass of the projectile, electron, and the projectile-electron reduced mass.

As is done in the BEA theory,[1,4] this cross section is integrated over a Fock distribution of bound electron velocities v_2, over ΔE, and finally the cross section is summed over electron shells:

$$\frac{d\sigma}{dE_x} = \sum_i n_i \int_{U_i + E_x}^{\infty} d\,\Delta E \int_0^{\infty} \frac{32\, v_s^5\, v_2^2\, dv_2}{\pi\,(v_2^2 + v_o^2)^4} \frac{d^2\sigma(E_x, \Delta E, v_1, v_2)}{dE_x d\Delta E} \tag{4}$$

where U_i is the binding energy of shell i, $1/2mv_s^2 = U_{s1}$ is the "idealized" or Slater rule value of this binding energy,[4,10] and n_i is the number of electrons occupying shell i.

This rather complicated expression may be evaluated approximately in systems where $v_1 < v_K$. The condition $\Delta E <$ a limits the integral to range from v_2^o to infinity where v_2^o is given by:

$$\frac{1}{2} mv_2^{o2} = E_2^o \approx \frac{(\Delta E - 4T)^2}{16T} \tag{5}$$

where $T = 1/2mv_1^2 = E_1 m/A_1M$. As long as E_2^o is much larger than ΔE, U_s, and 4T, the cross section is given by:

$$\frac{d\sigma}{dE_x} = \sum_s n_s \frac{0.004U_{SL}^{5/2}\,(U_S + E_x)\, Z_1^2}{E_2^{o3.5}\quad E_x\, T} \text{(barns/keV)} \tag{6}$$

where all energies are in keV.

The thick target RI yield obtained using Eq. (4) and Merzbacher's formula[11] is shown for 12-33 MeV O+Zr and O+Au collisions in Fig. 1. These results are based on numerical evaluation of Eq. (4) are identical with results using Eq. (6) for $E_x \gtrsim 20$ KeV.

RI should be important for slow ion-atom collisions because the initial electron velocity v_2 is large, and the acceleration is large. The major part of the cross section comes from near backscattering collisions between the projectile and electron. This can be seen if we use the maximum acceleration $|\vec{v}-\vec{v}'| = 2v \approx 2v_2$, in Eq. (1) and make an approximate evaluation, again assuming $E_2^o >> U_s$, ΔE, 4T. We obtain 0.006 for the constant in (6) instead of 0.004 thus the average acceleration can be considered as 82% of the maximum acceleration.

Despite these expectations, the theoretical thick target yield of RI falls short of the experimental yield. It is not known whether these continua are due to MO x rays or some other kind of bremsstrahlung. However, these calculation appear to rule out RI.

Finally let us comment on the applicability of these results. Since these equations are based on the atomic BEA theory, we can expect these results to be valid only when $Z_1 << Z_2$. This is nearly fulfilled in the case of O + Zr and O + Au collisions. The second condition is that $E_2^o \lesssim 200$ keV. For $E_2^o > 255$ keV, clearly the problem should be handled relativistically. Since this was not done here, it is not known how this affects the final thick target yields.

FOOTNOTES AND REFERENCES

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FIGURE CAPTION

Figure 1. Experimental absolute yield (solid) and RI yield (dashed) for 33 MeV O+Zr and 21 MeV O+Au. Spectra taken at other ion energies show qualitatively similar behavior.

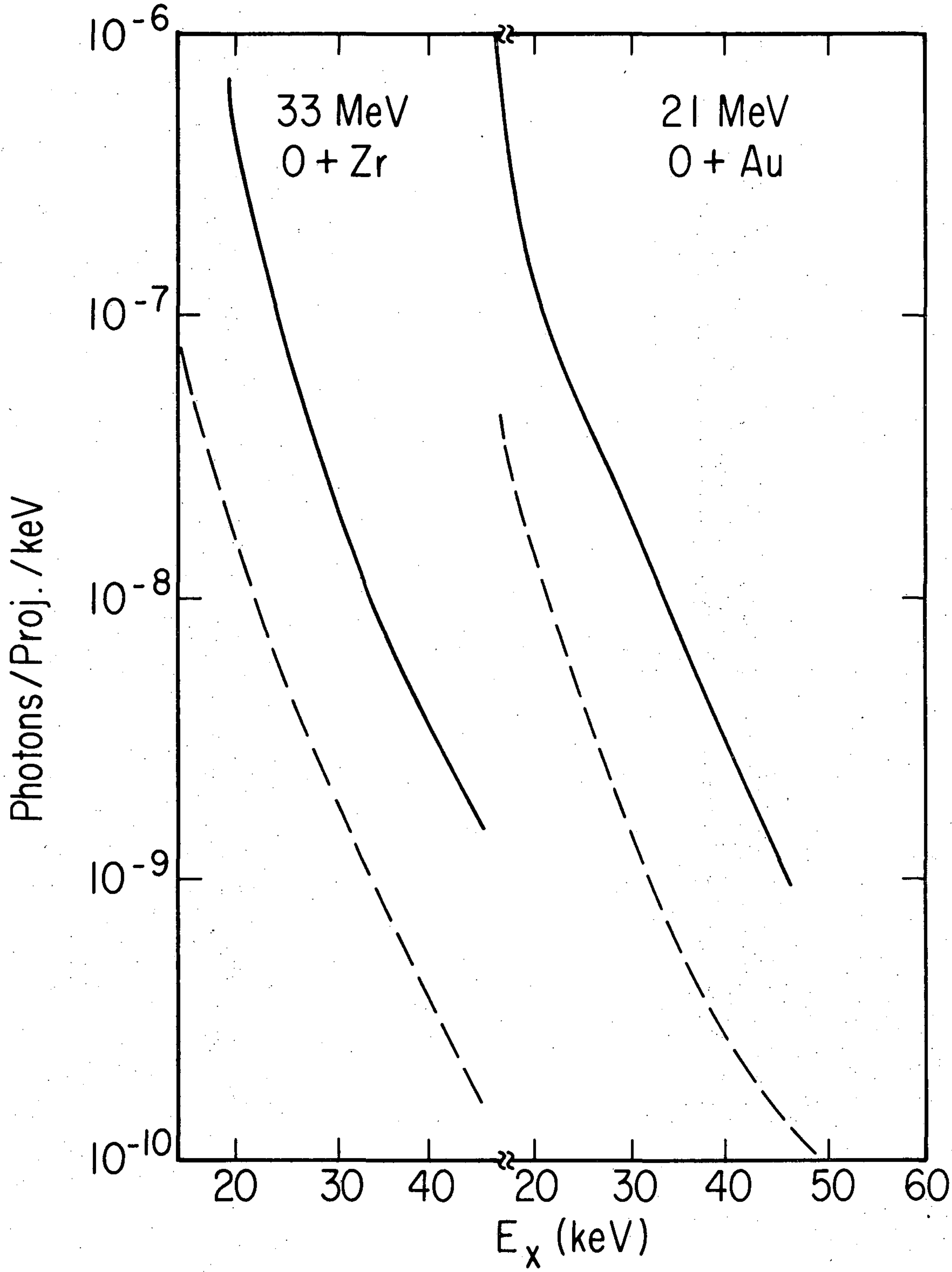

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Fig. 1

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