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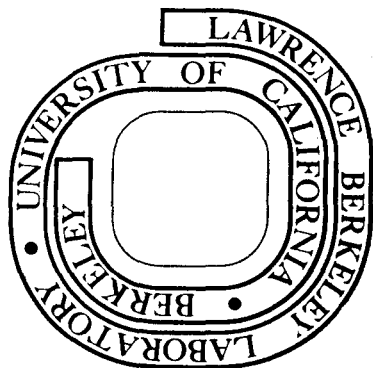
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IN HEAVY ION COLLISIONS

R. Anholt and T. K. Saylor

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ANOMALOUS X-RAY CONTINUA IN HEAVY ION COLLISIONS*

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ABSTRACT

X-ray continua have been observed in 33 MeV ^{16}O , 60 MeV ^{35}Cl , and 200 MeV ^{84}Kr encounters which have nearly identical yields per Zr K vacancy. Equally intense yields per Kr K vacancy have also been observed in 200 MeV $^{84}\text{Kr} + \text{KCl}$, Ti, and Ni encounters. These observations tend to preclude the molecular orbital x ray interpretation of these continua. We compare with theoretically calculated yields of molecular orbital x rays and bremsstrahlung.

During a sufficiently slow encounter between a heavy ion and a target atom, the electronic energy levels form molecular orbitals, and if inner shell vacancies exist, they may radiate during the collision emitting what are called molecular orbital (MO) x rays. Since the MO energy levels change with the internuclear distance, and the transition may occur at any point in the collision, continua instead of sharp lines are observed. X-ray continua have been observed in many systems and the MO interpretation has been born out by comparison with theory^{1,2,3} and measurement of the Doppler shift and angular distribution^{4,5} of these continua.

The MO model leads us to expect that the continua spectra taken in very asymmetric collisions (e.g. $O + Zr$) should not have similar shape and magnitude to a spectrum taken in a near symmetric collision. With the former example, the spectrum should approach an endpoint much lower in x ray energy. Due to dynamical line broadening considerations,² the spectra will tail beyond the expected endpoint at the united atom (UA) transition energy, but with the endpoints in the two systems so far apart (23 and 63 keV), the two spectra should be distinguishable. However, we observe that when plotted per separated atom (SA) K vacancy, these continua have nearly identical shape and magnitude. In this paper we discuss the MO interpretation and various bremsstrahlung processes that give rise to continua. At present, no model is available that accounts for the remarkable similarity of these spectra.

Figure 1 shows measured thick target yields per SA K vacancy for O , Cl , and $Kr + Zr$ and 200 MeV $Kr + KCl$, Ti , and Ni . Experimental details are similar to those previously published.¹ We report mainly two

observations: The yield per SA vacancy (1) is independent of the atomic numbers of the projectile (Z_1) for the same target and the target (Z_2) for the same projectile, and (2) appears qualitatively to be independent of beam energy. In our experiments, nearly identical yields were obtained with ions ranging from 1.3 to 2.4 MeV/amu (a 50% change in velocity). The uncertainty in the yields per vacancy is approximately 50% also; hence, writing the yield as proportional to the projectile velocity to the n th power, the data allows us to place $|n| < 1$.

Endpoints in MO x ray continua have rarely appeared at the UA limit and therefore the qualitative similarity in these spectra is not important. The quantitative similarity, however, is important and may indicate that some process other than MO x rays is producing these continua. We have considered the contributions from electronic pile-up, nucleus-nucleus bremsstrahlung (NNB), radiative electron capture, and Compton scattered γ -rays. Aside from the fact that the yields from these processes can be estimated and shown to be negligible, none of these fit the observations listed above. Electronic pile-up, NNB, and Compton scattered γ -rays would not give the same yield per SA K vacancy under a variety of different beam energies and projectile-target combinations. While our observations will not eliminate the possibility that the Kr + KCl, Ti, and Ni data may be due to radiative electron capture (REC) that effect cannot give the same yield for O, Cl, and Kr + Zr since the different projectile there will give much different spectra. Based on work by Kleber and Jakubassa,⁶ we have made theoretical calculations of REC for the Kr work. The yields decrease rapidly beyond the peak at 15.6 keV and beyond 25 keV, they are less than 10^{-9} photons/proj./keV everywhere.

Figure 2 shows that the yield of NNB⁷ and secondary electron bremsstrahlung (SEB)⁸ are insignificant compared to the experimental yield. We also give an estimate for another kind of bremsstrahlung called Radiative Ionization (RI).¹⁰ Whereas SEB occurs when electrons ejected into the continuum collide with other target nuclei, RI occurs when the electron is ejected from the target atom and is analogous to inner bremsstrahlung in β^- decay.¹¹ If we have a cross section $d\sigma(\vec{v}_1, \vec{v}_2, \vec{v}_2')$ for an electron with velocity \vec{v}_2 colliding with a projectile ion of velocity \vec{v}_1 , scattering with velocity \vec{v}_2' , the bremsstrahlung is given by:

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

where $\alpha = 1/137$, $c^2 |\Delta\beta|^2 = |\vec{v} - \vec{v}'|^2$, and \vec{v} and \vec{v}' are the relative velocities before and after the collision. Following Gerjuoy,⁹ (1) is integrated to obtain a cross section $d^2\sigma(E_x, \Delta E, v_1, v_2)/d\Delta E dE_x$ which is then integrated over a Fock distribution of velocities v_2 and over ΔE to obtain the estimates shown.¹² RI should be important for these slow ion velocity systems because in order for the electron to be ionized, there must be an initial large acceleration, and therefore a large bremsstrahlung yield. Like the SEB estimates, these calculations can be trusted when $Z_1 \ll Z_2$, the O + Zr case. There, this yield lies a factor of ten or more below experiment. RI has many of the right features (e.g., yields per K vacancies independent of velocity, and the projectile-target combination) to explain these spectra. More accurate calculations are needed (especially calculations that can be reliably extended to symmetric collisions) before we can conclude that these continua are not due to RI.

The two collision yield of MO x rays in these systems is consistently smaller than the experimental yield observed. The quasi-static theory of one collision MO x rays¹ coming from vacancies that are created then radiate in the same collision can predict the Kr + Zr and Kr + Ni spectra to within a factor of two or better, but fails for other cases. Although this theory predicts experimental MO x ray yields successfully in a great many cases, there are theoretical objections to it and even cases where it does not fit.¹³ The main objection to the theory is that it is a static theory and unlike for the two collision yield where dynamical calculations have been done which showed that the static theory gives reliable results between the SA and UA limits,² the dynamic theory of one collision MO x rays has not yet been developed.

Thorson and Choi¹⁴ have recently suggested that a dynamical process involving emission of "transiently formed vacancies" may give a greater one collision yield than the part predicted by the quasi-static theory. They recognized that while the excitation of lso electrons is very inefficient giving few vacancies at the end of the collision, the probability of having a vacancy during the collision when the two nuclei are within say the K shell radius of one another, is comparatively large. X rays emitted by these transient vacancies would give a shapeless continuum, with no endpoint at the UA transition energy, but it is not clear whether the yield per SA K vacancy would be identical under a variety of conditions. No calculation of this yield has been done however and we leave this possibility open.

In conclusion, we have observed continua that have yields per SA vacancy independent of the projectile-target combination and roughly

independent of velocity. At this point, all theories of bremsstrahlung processes and MO x rays fail to predict the magnitude of these x ray yields and the remarkable similarity under a variety of conditions. The authors feel that the Radiative Ionization and one collision MO x ray process (especially emission of transiently formed vacancies) are the most likely candidates to explain these continua, though the theory of these processes needs considerable improvement before the magnitude of the x ray yield can be predicted with any certainty.

These observations are not unique to the two systems presented in this work. In .75 MeV/a.m.u. C, O, Cl, and Br bombardments of Au, Stott and Waddington¹⁵ have noted nearly identical continuum yields per Au L vacancy in the region between 15 and 60 keV. The present experiments were partly inspired by their work. We have repeated their experiments with O, Ar, and Kr bombardments of Au, Pb, and U and have confirmed this trend. We have also observed identical yields per Br K vacancy when KBr was bombarded with both O and Kr ions. Although this trend was not widely observed in the low velocity work of Meyerhof et.al.¹ there are two cases where the one collision yield was dominant, namely Br + Ti and Br + Al, where identical yields per Br K vacancy were observed. In most of that work, the two collision yield was dominant and this may be the reason why this effect was not widely observed.

The observations presented in this paper make an important contribution to the data on x ray continua from heavy ion collisions. The origin of these continua and the close similarity in the magnitude and shape using different projectile-target combinations needs to be understood before we can infer anything from "MO x ray continua" about the

atomic and molecular processes that go on in heavy ion collisions.

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FOOTNOTES AND REFERENCES

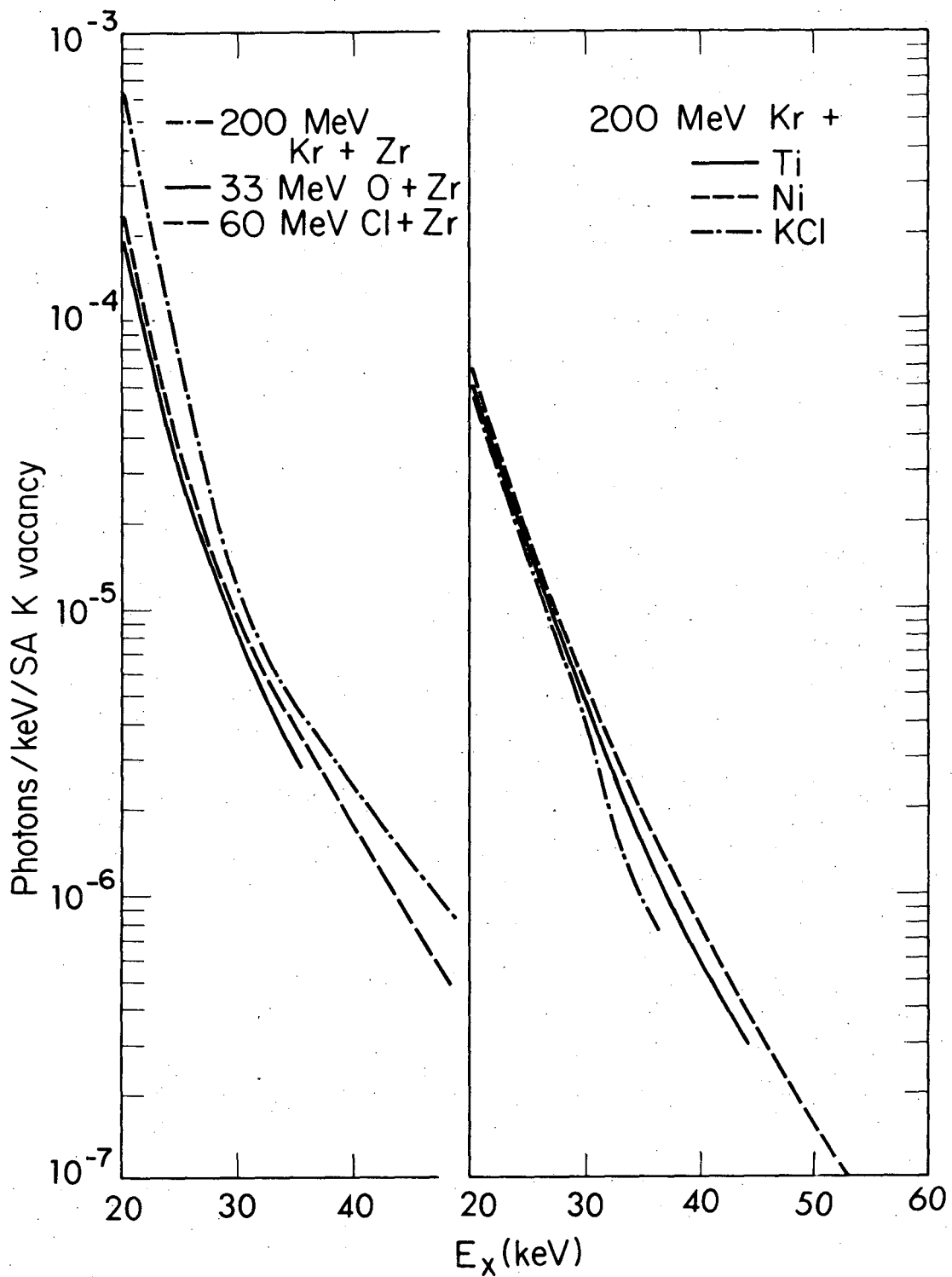
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FIGURE CAPTIONS

- Fig. 1. Left: Yield per Zr K vacancy for 33 MeV O (solid), 60 MeV Cl (dashed), and 200 MeV Kr + Zr (dash-dot). Right: Yield per Kr K vacancy for 200 MeV Kr + Ti (solid), Ni (dashed), and KCl (dash-dot).
- Fig. 2. Absolute yields for 33 MeV O + Zr, 200 MeV Kr + Ti, and 200 MeV Kr + Zr. Dashed: Secondary Electron Bremsstrahlung (SEB) and Radiative Ionization (RI) yields. Dotted: Nucleus-Nucleus Bremsstrahlung (NNB). Solid lines: two collision (TCMO) and one collision MO x ray yield (OCMO).



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Fig. 1

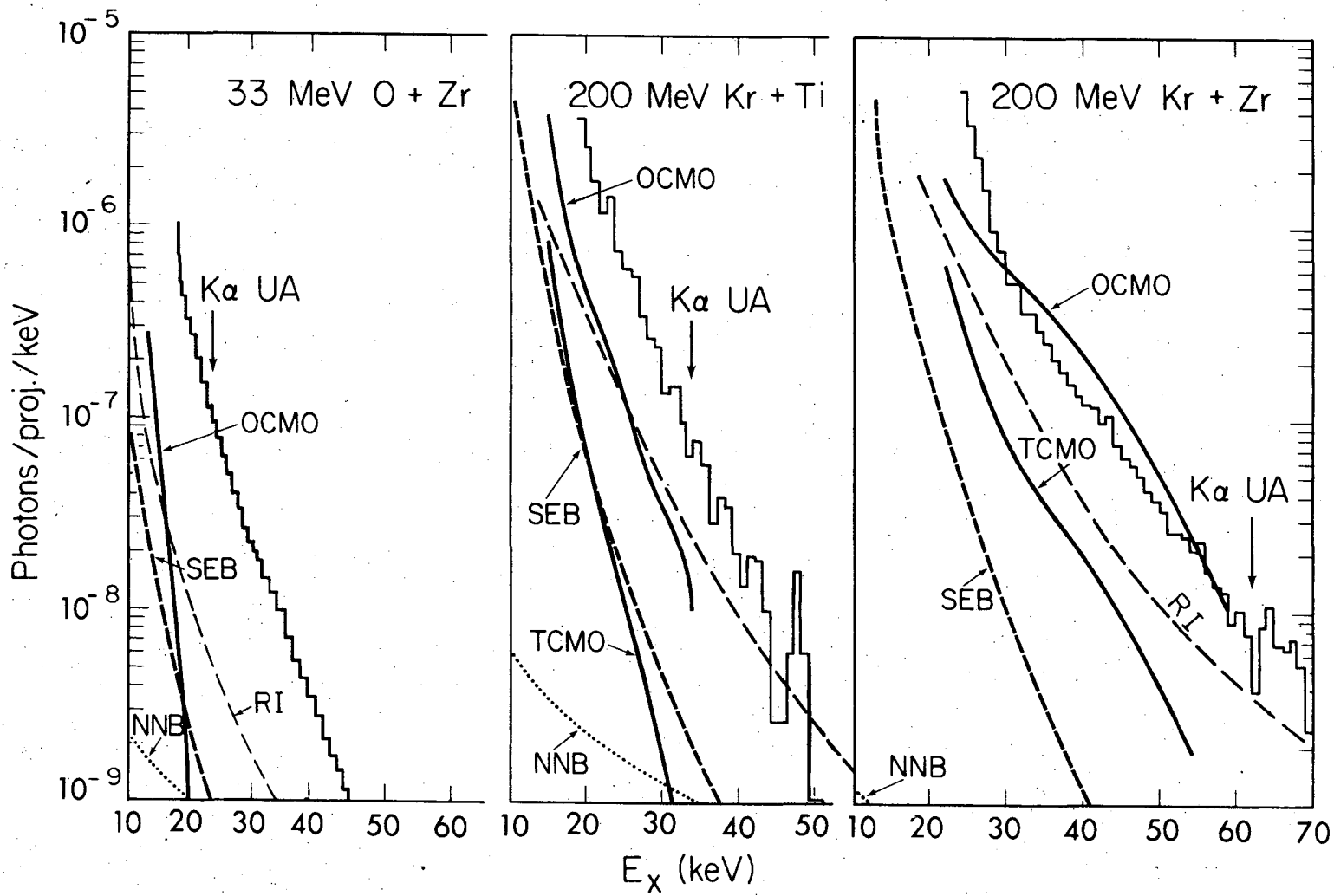


Fig. 2

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