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Molecular-Orbital K X-Ray Formation in Heavy-Ion Collisions*

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In order to complete the identification of molecular-orbital K x-ray spectra, we have worked out the expected spectral yields and compared them with experimental spectra produced by 30- and 60-MeV Br and 82-MeV I beams. Independently, we have determined the dominant mechanism of molecular-orbital K x-ray production in 30-MeV Br + Br collisions by diluting the Br density in a solid target.

The identification[1] of molecular-orbital (MO) K x rays is incomplete[2] without fitting the shapes and intensities of the observed spectra. We have computed the spectral yields expected for the one- and two-collision mechanisms discussed in Ref. 1 and have fitted experimental spectra for symmetric and asymmetric collisions. Independently, we have determined the dominant mechanism of MO K x-ray production in 30-MeV Br + Br collisions.

Under the static approximation, the cross section for MO x-ray production in a one-collision process in which a $1s\sigma$ vacancy is first made and then filled with emission of a photon of energy E_x is given by

$$d\sigma_{\mathrm{MO}}^{(1)}/dE_x = \int db\, 2\pi b[P(b,t_1)+P(b,t_2)] \times (dR/dE_x)(v_R\tau_x)^{-1}. \qquad (1)$$

Here $P(b,t)$ is the probability that during the collision a $1s\sigma$ vacancy is created at any time before t. The two times at which a trajectory of impact parameter b intersects a given radial distance R are denoted by t_1 and t_2. The decay probability of the vacancy during a time interval dt following t_1 or t_2 is equal to $dt/\tau_x = dR/v_R\tau_x$, where $\tau_x(R)$ is the mean life of the vacancy and $v_R(b,R)$ is the radial component of the relative nuclear velocity. In certain theoretical approximations[3] the symmetry of the electron distribution about the axis of the trajectory hyperbola permits the simplification $P(b,t_1)+P(b,t_2)=P(b)$, where $P(b)$ is the total probability that a $1s\sigma$ vacancy is created during the collision. By integrating over b at fixed E_x (i.e., R) from 0 to $b'=(R^2-DR)^{1/2}$, where D is the distance of closest approach in a head-on collision, and by converting cross sections to thick-target yields, one finds that to a good approximation the spectral yield per projectile for the one-collision process is given by

$$\frac{dy_{\mathrm{MO}}^{(1)}}{dE_x} = \frac{y(1s\sigma)F(b')(dR/dE_x)}{v_1\tau_x(1-D/R)^{1/2}}, \tag{2}$$

$$F(b') \equiv \int_0^{b'} db\, \frac{bP(b)}{(1-b^2/b'^2)^{1/2}} \left[\int_0^\infty db\, bP(b)\right]^{-1}. \tag{3}$$

The thick-target yield per projectile $y(1s\sigma)$ for direct excitation of the $1s\sigma$ MO can be obtained from experiment.[4] Expressions for $P(b)$ in the literature (e.g., Ref. 3) have not been computed for $1s\sigma$ excitation, except for[5] $Z_1 = Z_2 = 1$. From the latter work we parametrize, approximately, $P(b) \propto (1+Ae^{b/a})^{-1}$, where $A \approx 1$ and $a \approx a_K$ (Bohr K radius).

In the two-collision process the projectile obtains a K vacancy in a prior collision (yielding on the average y_K vacancies per projectile) which is transferred in a subsequent collision within the lifetime τ_K of the vacancy to the $1s\sigma$ MO by the process discussed by Meyerhof.[6] The spectral yield per projectile is

$$\begin{aligned}\frac{dy_{\mathrm{MO}}^{(2)}}{dE_x} &= y_K f(w) n \int_0^{b'} db\, 2\pi b v_1 \tau_K 2 \frac{(dR/dE_x)}{v_R \tau_x} \\ &= 4\pi y_K f(w) n \frac{\tau_K}{\tau_x}\left(1-\frac{D}{R}\right)^{1/2} \frac{R^2\, dR}{dE_x}.\end{aligned} \tag{4}$$

Here n is the number of target atoms per unit volume and v_1 the projectile speed. The function $f(w)$ is equal to w or $1-w$, depending on whether the projectile is the lower- or higher-Z collision partner, where w has been evaluated in Ref. 6; it is equal to $\frac{1}{2}$ for a symmetric collision. The additional factor 2 is due to the two crossings of a given R by each trajectory.[7] Equation (4) contains no adjustable parameters. It has been derived differently and for the special case of symmetric collisions.[7-9]

Equations (2) and (4) imply that the MO K x-ray yields for the one- and two-collision processes should be proportional to n [since $y(1s\sigma) \propto n$] and $y_K n$, respectively. Since, approximately, $y_K \propto n$, varying the target atom density can establish the dominant mechanism directly. This test can be made with solid targets,[10] provided the other target atoms do not contribute to the MO yield. We have found that if K or Cl is bombarded with 30-MeV Br, the projectile K-vacancy yield, which is due to direct $1s\sigma$ MO excitation in that case,[6] is only 10^{-3} of the 30-MeV Br + Br K-vacancy yield. Hence we bombarded targets of solid Br (on a refrigerated Al backing) and of KBr + KCl mixtures (evaporated onto Al backings) with 30-MeV Br. After correction for absorber and efficiency effects the spectra shown in Fig. 1(a) are obtained. Subtracting the expected[2,11] nucleus-nucleus bremsstrahlung background [curves B, computed from Eq. (II.E.13) of Alder *et al.*[12]], one can deduce the net integrated MO K x-ray yields y_{MO}. Figure 1(b) shows that the ratio $y_{\mathrm{MO}}(E_x = 27-50\text{ keV})/y_K$ is approximately proportional to n (normalized relative to pure solid Br). (A better proportionality is obtained if the one-collision yield, estimated as indicated below

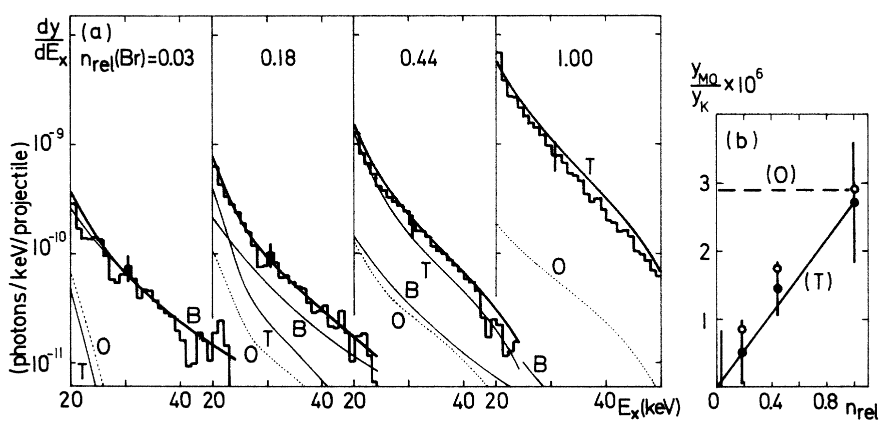

FIG. 1. (a) Corrected x-ray spectra from 30-MeV Br bombardment of various Br targets. Room background subtracted. Typical systematic errors are $\pm 30\%$. The relative Br density corresponds to the following targets: 1.00, pure Br; 0.44, pure KBr; 0.18, 50% KBR + 50% KCl; 0.03, 10% KBr + 90% KCl. In each case, B, O, and T are the computed bremsstrahlung and one- and two-collision MO spectra, respectively. The darker curves give $B+O+T$. (b) Ratio of integrated MO K x-ray yield ($E_x = 27$ to 50 keV) to beam K-vacancy yield versus relative Br density. Lines O and T give the relationships expected for one- and two-collision mechanisms, respectively. Open symbols, total MO yield; solid symbols, total MO yield minus estimated one-collision contribution.

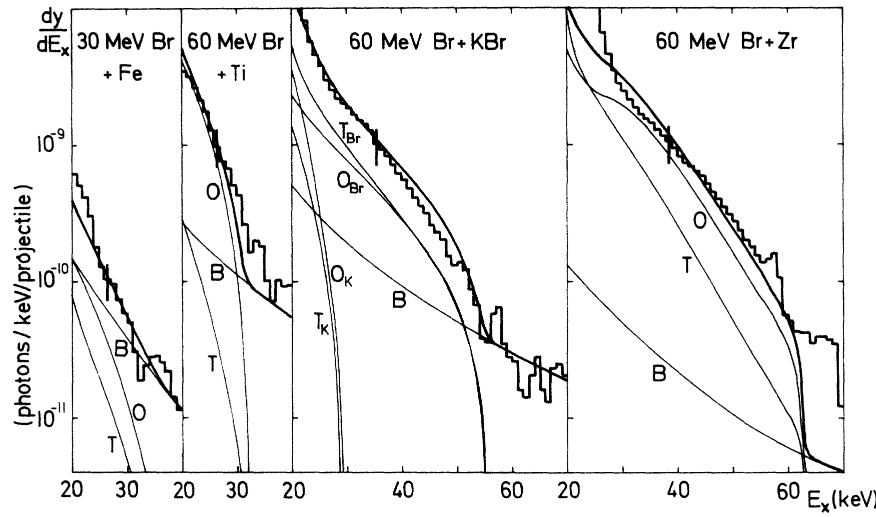

FIG. 2. Continuum x-ray spectra from Br bombardment. Room background and background due to nuclear γ rays subtracted. Notation as for Fig. 1(a). O_{Br} and O_K denote separate one-collision contributions from Br and K target atoms. The darker curves give $B+O+T$.

and denoted by O, is also subtracted.) This indicates a dominant two-collision mechanism for 30-MeV Br + Br collisions. Independent confirmation is obtained by computing the expected spectral yields from Eq. (4). To relate R and E_x we use a calculation of Müller, Rafelski, and Greiner[13] for the Br + Br system. To estimate τ_x we use the empirical relation[14] between the radiative K-vacancy lifetime for *atoms* and the $K\alpha$ x-ray energy. This yields the correct τ_x at the separated- and united-atom limits, but is only approximate in between. The calculated curves T in Fig. 1(a) show that in situations in which the two-collision process should dominate, this prescription is reasonably successful in fitting the experimental results.

Since the quantity $y_K f(w)$ in Eq. (4) decreases rapidly with increasing asymmetry,[6] the one-collision process should become dominant in sufficiently asymmetric collisions. To demonstrate this, we present in Fig. 2 various experimental and computed spectra. The higher-energy portions of the observed spectra have large uncertainties due to the subtraction of background from Coulomb-excited nuclear γ rays which become intense at 60-MeV bombarding energy. We obtain reasonable fits to the very asymmetric spectra by setting $A=1$ and a equal to the Bohr K radius of the higher-Z collision partner in the expression for $P(b)$ in Eq. (3), but using no other adjustable constants in Eq. (2). A similar prescription is then applied to the symmetric spectra, with good success. In these computations we used relations between R and E_x from Ref. 13

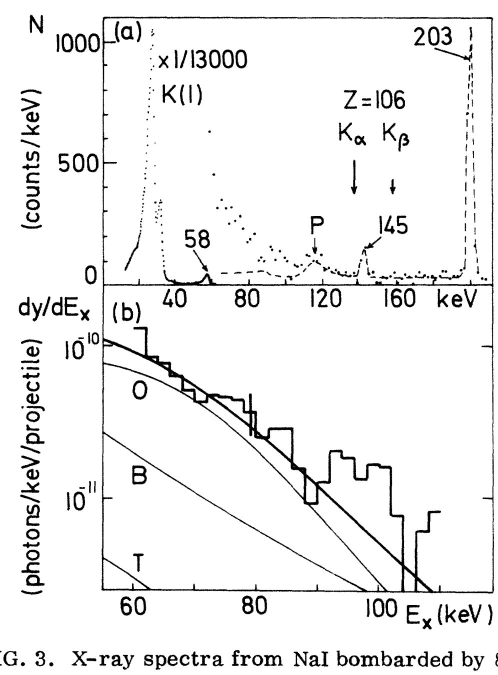

FIG. 3. X-ray spectra from NaI bombarded by 82-MeV I. (a) Room-background–subtracted data, 17-cm^3 Ge(Li) detector, 0.3-mm stainless steel absorber. Iodine K lines and Coulomb-excited γ rays are indicated. Dashed line is assumed background under continuum; P is a backscattering peak. Arrows give united-atom K x-ray limits. (b) Corrected x-ray spectrum. Above 100 keV the spectral shape is unreliable. Notation as for Fig. 1(a). The dark curve gives $B+O+T$.

and interpolations from Helfrich and Hartmann.[15]

Relative to Eq. (2), Eq. (4) contains the additional Z-dependent factor $\tau_K R^2$ which scales approximately as Z^{-6}. Hence at higher Z the one-collision process should dominate MO K x-ray formation even in symmetric collisions. To check this, we bombarded thick, evaporated NaI targets with 82-MeV I [Fig. 3(a)]. Unfortunately, nuclear γ rays from ^{127}I (58, 145, and 203 keV) are strongly Coulomb excited. After convincing ourselves that the continuum between the 58- and 145-keV γ rays is not due to pileup, we have extracted an x-ray band which we believe to be due to the I+I MO K x rays [Fig. 3(b)]. Theoretical curves were computed using an R-E_x relation from Ref. 13. The fit to experiment is reasonable and suggests the importance of one-collision $1s\sigma$ excitation in MO K x-ray production in higher-Z($z \gtrsim 50$) collisions.

There is a need to examine the basic assumptions underlying Eqs. (1) and (2) and to include dynamic effects[16] in Eqs. (2) and (4). Nevertheless, we believe that the totality of the present work completes the identification of MO K x rays.

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Emission Profiles of Laser-Induced Optical Satellite Lines in a Helium Plasma*

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We have measured the spectral line profiles of the optical satellites emanating from the $(2^3S, 2^3P)$-$(4^3S, 4^3P)$ excited state manifolds of a low-pressure helium plasma. These satellites are induced by the presence of a CO_2 laser field. Detailed spectra are presented for the 2^3P-4^3S, 4713-Å He I allowed line and its associated near satellite. A theoretical model, valid for large, near-resonant interactions is described. This theory is seen to be in good agreement with the experimental results.

Optical satellites,[1-4] which appear in plasma emission spectra symmetrically flanking a forbidden ($\Delta L = 0, \pm 2$) atomic line, contain information from which the intensity and frequency spectrum of plasma fluctuations might be obtained. However, a precise determination of such a frequency spectrum requires a knowledge of what we call the inherent satellite line profile. For