urations ^{31}Si(g.s.) = ^{28}Si(g.s.) + *nnn* and ^{11}B(g.s.) = ^{8}B(g.s.) + *nnn* are unlikely, theoretical results will be in better agreement with experimental data once the correct values of S_1S_2 are included. The present calculation also verifies the statement of the authors of Ref. 7 that the low cross section for *nnn* transfer follows the trend of high-energy heavy-ion reactions of favoring the transfer of bound clusters. It is worth pointing out in this connection that because of the smaller binding energy of the assumed *nnp* cluster (19.7 MeV) compared to that of the *nnn* cluster (38.5 MeV) in the projectile, the (^{11}B, ^{8}Be) reaction on the same target gives a calculated differential cross section about 12 times larger (6.35 μb/sr) compared to that of the (^{11}B, ^{8}B) reaction (0.55 μb/sr). In planning multinucleon transfer experiments, dynamic effects such as this might be of considerable value to the experimenter.

In conclusion, we have shown that the explanations for the suppression or enhancement of heavy-ion-induced multinucleon-transfer reactions in terms of empirical T-selection rules only may be clouded by dynamic effects such as those caused by binding energies of the transferred clusters to the cores.

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Single-Collision Production of Quasimolecular X Rays in Heavy-Ion Encounters

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Remarkably large quasimolecular (molecular orbital) K-shell x-ray yields are found in 48-MeV S→ Ne encounters, unequivocally indicating that production of molecular-orbital x-rays can occur as a result of single-collision mechanisms. Gaseous and solid targets are found to give similar spectral shapes of the emitted continuum radiation.

In heavy-ion–atom collisions certain molecular states can be transiently formed. If there is a vacancy in the quasimolecular system electronic transitions between these states may lead to emission of quasimolecular [molecular orbital (MO)] x-ray continua.

Originally, a double-collision mechanism has been postulated[1]: In a first collision an inner-shell vacancy is somehow produced in the projectile ion and is then carried into a second collision where its decay may lead to the observed MO x-ray transition. The exclusiveness of this mechanism appeared to be backed up by recent experiments in gas targets; for example, Saris *et al.*[2] concluded that L-shell MO x rays from 300-keV Ar-Ar collisions are absent when the incident Ar ions have no initial L vacancy. Assumption of the double-collision mechanism implies that the initially produced vacancy must survive the time which elapses between the two collisions. However, since total lifetimes of vacancies and shell radii decrease strongly with increasing nuclear charge, Z, of ions, MO x-ray production would also decrease for heavier collision systems and would become difficult to observe for the heaviest projectile ions. Mokler, Stein, and Armbruster[3]

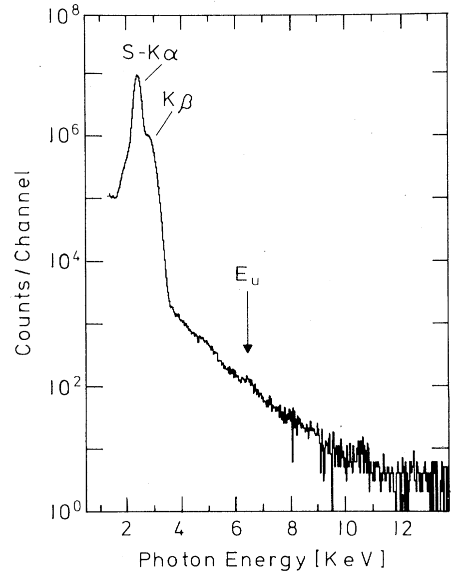

FIG. 1. X-ray spectra from collisions of 48-MeV sulfur ions of charge 7+ with Ne gas at 0.9 Torr, corrected for absorption effects. Because of the particular collision conditions (no initial K vacancy production at small impact parameters) no radiative-electron-capture peak is visible.

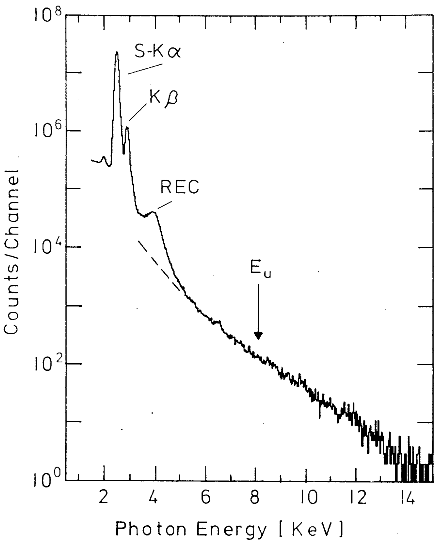

FIG. 2. X-ray spectrum from collisions of 55-MeV sulfur ions with 100-μg/cm^2 aluminum, corrected for absorption effects. REC: radiative electron capture; - - - MO x-ray spectrum after subtraction of REC.

indicated that a single-collision mechanism might be worth considering, i.e., production and decay of a vacancy during a single encounter. Meyerhof *et al.*[4] measured MO x rays from bombardment of thick solid targets and estimated contributions due to double and single collisions on the basis of various assumptions concerning excitation of the $1s\sigma$ MO. It is the purpose of this Letter to present experimental MO x-ray spectra for gas targets which prove the occurrence of single-collision mechanisms. We discuss some production mechanisms and include effects due to dynamic collision broadening.

Essentials of the experimental setup for the measurement of x-ray spectra from bombardment of thin, solid targets have been described previously.[5] In addition, for the present experiment, a windowless, differentially pumped gas cell with pressures of up to ~1 Torr Ne has been employed. A Si(Li) x-ray detector viewed the gas-beam interaction region over a length of 2 cm. Figure 1 shows an x-ray spectrum for 48-MeV sulfur ions with charge state 7+ incident on a 0.9-Torr-Ne-gas target. For comparison, Fig. 2 presents an x-ray spectrum for 55-MeV sulfur on 100-μg/cm^2 solid Al.

In the following, we elucidate the collision processes by discussing the high-energy MO radiation tails especially for x-ray energies $E_x \geq E_u$, where E_u denotes the transition energy of the ideally united collision system (united-atom energy). These tails, clearly visible in Figs. 1 and 2, have been identified in a recent paper[5] on the basis of a quantitative theory of dynamic collision broadening, in which only contributions from double-collision processes had been taken into account. Comparison of Figs. 1 and 2 demonstrates that in the systems studied here experimental MO tails, measured relative to the characteristic projectile x-ray line, are almost equally intensive in solid and gaseous targets. It is easily shown that independent of theoretical models the appearance of strong MO tails in gas targets can be explained only by single-collision processes; note that gas densities used are ~6 orders of magnitude smaller than those of solids and that lifetimes of S K vacancies are ~10^{-14} sec. In this experiment the incident beam (S^{7+}) does not have initial K vacancies; incidentally, this is also reflected in the virtual absence of the radiative-electron-capture peak.

Let us consider MO x rays with an energy $E_x \geq E_u$ for which the production cross section, σ_{MO}, has been worked out for transitions with the assumption that a vacancy exists prior to the collision.[5] However, since vacancies are produced *during* a collision, MO x rays may already occur in that same collision; in this case, the cross section for spontaneous and rotationally induced transitions is given by

$$d\sigma_{\mathrm{MO}}^{(1)}/dE_x = 4\alpha E_x(3\hbar^2c^2)^{-1}\int|\vec{\mathrm{D}}(b,E_x)|^2 b\,db,$$
$$\vec{\mathrm{D}} = \int_{-\infty}^{\infty} F(t)[E(t)/\hbar + i\vec{\Omega}(t)\times]\,\vec{r}_{fi}\exp\{(i/\hbar)\int_{-\infty}^{t}[E(t')-E_x]dt'\}dt, \tag{1}$$

where $\alpha = e^2/\hbar c$, and $F(t)$, $E(t)$, $\vec{\Omega}(t)$, and $\vec{r}_{fi}$ are vacancy amplitude, MO transition energy, internuclear rotation frequency, and dipole transition matrix element, respectively. For constant F one can add contributions from spontaneous and induced transitions incoherently; furthermore, if a vacancy is brought into the collision, F is unity and $\sigma_{\mathrm{MO}}^{(1)}$ from Eq. (1) becomes essentially identical with σ_{MO} from Ref. 5. A quantity easily measured in experiments is the ratio between projectile and MO x rays with $E_x \geqslant E_u$. In a gas target, and for constant F (see below), this ratio can be expressed by $f_1 \simeq \sigma_{\mathrm{MO}}\gamma_{\mathrm{MO}}/\pi R_u^2\omega_0\gamma_L$, where R_u is the united-atom K-shell radius, and ω_0 is the average fluorescent yield of the projectile K vacancies; γ_{MO} and γ_L are those fractions of vacancies which can give rise to MO x rays (in the same collision) and projectile x rays, respectively. These two fractions are not necessarily equal: For example, vacancies could be formed at internuclear separations, R, which are too large to allow any subsequent MO x-ray decays, and vacancies created early in the collision at sufficiently small impact parameters contribute to MO x-ray production, but can be transferred out of the projectile later in the collision. The ratio f_1^{sp} due to spontaneous transitions then becomes

$$f_1^{\mathrm{sp}} \simeq 0.22\gamma_{\mathrm{MO}}(\omega_0\tau_u\sqrt{\dot{\omega}}\gamma_L)^{-1}, \quad E_x \gtrsim E_u, \tag{2}$$

where τ_u is the radiative lifetime of the vacancy in the ideally united atom, and $\dot{\omega}$ is an average over the change of transition frequencies as a function of internuclear separation during the collision. It is illustrative to compare f_1 with the corresponding double-collision fraction, f_2, from Ref. 5:

$$f_2/f_1 \simeq \pi R_u^2 N v\tau_0\omega_0\gamma_L/\gamma_{\mathrm{MO}}, \tag{3}$$

where τ_0 is the radiative lifetime of the vacancy in the undisturbed projectile ion and N is the target density. For 48-MeV S on Ne we measure a fraction $f_1 = 4.4\times 10^{-5}$. Evaluation of Eq. (2) with $\omega_0 = 0.25$, $\tau_u = 7\times 10^{-15}$ sec,[6] and, according to the prescription given in Ref. 5, $\sqrt{\dot{\omega}} = 4\times 10^{18}$ sec^{-1} yields $f_1 = 1.2\times 10^{-4}\gamma_{\mathrm{MO}}/\gamma_L$, so that reasonable agreement with experiment would result for $\gamma_{\mathrm{MO}}/\gamma_L \simeq 0.36$. When we take the same ratio $\gamma_{\mathrm{MO}}/\gamma_L$ for 48-MeV S on Al, we obtain $f_2/f_1 \simeq 0.5$ ($f_1 \simeq 5\times 10^{-5}$, $f_2 \simeq 2.7\times 10^{-5}$); this implies that in the present experiment single- and double-collision processes are roughly of equal importance. This is clearly corroborated by our data, since the fractions measured in Al (4×10^{-5}) and Ne (4.4×10^{-5}) are close to each other.

The fraction f_2 decreases strongly with increasing Z; contributions due to spontaneous emission scale as[5] $f_2 \propto (v/Z^7)^{1/2}$, where v is the ion velocity. It is a question of major interest to specify general conditions for which the single-collision process becomes dominant. This requires careful analysis of the ratio $\gamma_{\mathrm{MO}}/\gamma_L$, i.e., of the actual single-collision mechanisms. Let us first consider K-shell-vacancy production in symmetric systems ($Z_1 = Z_2$), where we distinguish ionization processes along the following orbitals: (A) united 1s at small R, (B) undisturbed 1s at $R \gtrsim R_{\mathrm{MO}}$, (C) molecular 2$p\sigma$, and (D) 2$p\pi$ with rotational coupling to 2$p\sigma$ at small R. One must also allow for Demkov-type vacancy transfer[7] between target and projectile 1s orbitals which is expected to occur near $R \simeq R_{\mathrm{MO}}$, where R_{MO} is the maximum internuclear separation for which MO effects can develop. All four processes A–D can give rise to characteristic x rays, but only A and B can contribute to K-shell MO x rays with $E_x \geqslant E_u$.

For the largest velocities near $v_0 Z$ for which MO effects can occur, Coulomb ionization of undisturbed K electrons with binding energy E_B takes place mainly at separations near $R_C \simeq \hbar v/E_B$ which reach or exceed R_{MO}. In this case, we can calculate f_1 from Eq. (1) with $F = \mathrm{const}$ and processes B and C dominate over A and D. It may further be deduced that with adequate consideration of Coulomb-ionization and Demkov-transfer probabilities the ratio $\gamma_{\mathrm{MO}}/\gamma_L$ will not be too small compared to unity and may be estimated as $\gamma_{\mathrm{MO}}/\gamma_L \gtrsim 0.2$. Evaluation of Eq. (3) then shows that $f_1 > f_2$ should be realized for values of Z as low as ~ 10.

In the present S → Ne experiment, we have $v = 0.48 v_0 Z$ and MO x rays come mainly from process B. The ratio of ionization cross sections for processes B and C from the scaled Born approximation is close to $\frac{1}{40}$, and the Demkov-transfer probability [$1s$(Ne)-$1s$(S)] is 0.1.[7] This yields an approximate theoretical estimate $\gamma_{\text{MO}}/\gamma_L \simeq 0.25$ which is compatible with the value 0.36 deduced from experiment.

For lower collision velocities, decrease of R_{C} causes process B to fade away, whereas D will be more influential. Since the sum of cross sections for processes D and C becomes much larger than the cross section for A almost all K vacancies which emerge from the collision are produced by molecular effects and have never existed in the united K shell at $R < R_{\text{MO}}$. Thus, $\gamma_{\text{MO}}/\gamma_L$ will be drastically reduced especially for the higher MO x-ray energies near E_u. The ratio $\gamma_{\text{MO}}/\gamma_L$ will then reflect the cross-section ratio of total K-vacancy production and direct Coulomb ionization of the $1s\sigma$ orbital with binding effects taken into account. It will then become increasingly difficult to observe single-collision K-shell x rays for any Z in most of the adiabatic collision range.[2,8]

It is interesting to point out that in low-velocity collisions $1s\sigma$ vacancies are created at small R so that $F(t)$ is nearly zero for the first half of the collision. Solution of Eq. (1) for $E_x \geqslant E_u$ then predicts that the width parameter, H,[5] of the x-ray tail becomes almost precisely twice as large compared to cases where a vacancy is already present before the $1s\sigma$ MO is formed. Experimental tests of such an effect would contribute to our understanding of vacancy formation processes in heavy-ion collisions.

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Soft-X-Ray Amplified Spontaneous Emission via the Auger Effect*

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It is proposed that amplified spontaneous emission in the soft-x-ray region can be obtained using inner-shell population inversions arising from the Auger effect. I treat Na^+ and show that with present-day technology it appears possible to generate a pulse of 10^{-5} to 10^{-7} J in less than a nanosecond at 410 Å. The possible effect of interatomic Auger processes in the solid is discussed but high-electron-density effects are not accounted for.

In the past several years many schemes for producing x-ray lasers have been advanced.[1-9] The schemes differ in their treatment of Auger widths. A large Auger width for the upper lasing level has two detrimental effects. It lowers the gain cross section

$$\sigma_g = \lambda^2 A/4\pi^2\Delta\nu = \lambda^2\Gamma_R/2\pi(\Gamma_1+\Gamma_2), \tag{1}$$

where λ is the wavelength of the transition, A is the radiative transition rate ($A = 1/T_R = \Gamma_R/\hbar$), $\Delta\nu$ is the natural linewidth [$\Delta\nu = (\Gamma_1+\Gamma_2)/h$], and Γ_1 and Γ_2 are the total widths of the individual levels. In addition one has an equation for the number of inner-shell vacancies per unit volume,

$$dN/dt = P - N\Gamma/\hbar, \tag{2}$$

where P is a pumping term. The solution $N = (\hbar P/\Gamma)(1 - e^{-\Gamma t/\hbar})$ clearly indicates that P must increase linearly with Γ to attain a given number density.

The idea advanced here is to use the Auger effect to produce an inner-shell population inversion. In an Auger transition certain final-state terms are preferentially populated. For such an inversion in final-state terms to be useful,