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Anisotropic Emission of Noncharacteristic X Rays from Low-Energy I-Au Collisions

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The x-ray emission for 6- to 60-MeV iodine bombardment on thin Au targets was measured. Spectra, cross sections, and angular dependence of x-ray emission are reported. Special emphasis is placed on the noncharacteristic radiation formerly interpreted as M radiation of a quasiatom with an effective atomic number of 132. The emission of this radiation is found to be nonisotropic strongly supporting the model of induced emission in the collision molecule.

X-ray spectra from heavy-ion–atom collisions may show both characteristic lines of the separated collision partners, as well as broad noncharacteristic bands. In slow collisions the noncharacteristic x rays have been ascribed to radiative transitions between molecular orbitals (MO's) of transiently formed collision molecules.[1,2] Such noncharacteristic x rays, for instance, were observed at 11-MeV iodine bombardment on thick gold targets.[3,4] In these measurements the noncharacteristic band revealed a broad peak at about 8 keV. This energy corresponds to $4f-3d$ transitions[5] in a united atom. Therefore, the x-ray band has been interpreted as M radiation from a short-lived "superheavy quasiatom" with an effective atomic number $Z=Z_1+Z_2=132$. A double-collision mechanism is assumed to be responsible for these x rays. In a first collision an L vacancy is produced in the moving I ion. In a second collision this inner-shell vacancy can decay in the I-Au collision molecule. The existence, as well as the origin, of these x rays has been confirmed by measurements at the University of Rochester.[6] Nevertheless, this MO x-ray emission is still not completely understood. Two critical features remain unexplained: first the high yield and second the spectral distribution.

In order to get more information on the emission mechanism we investigated in more detail the I-Au collision system at the Cologne tandem accelerator. Using thin Au targets and a high-resolution Si(Li) detector we determined the spectral distribution more precisely and we measured the x-ray production cross sections. In addition, the angular dependence of the x-ray emission was studied.

The experiments were performed with different setups. For spectral-distribution and cross-section measurements a conventional arrangement was used, see, e.g., Ref. 4 (target angle $\alpha = 45°$, x-ray emission angle $\theta = 90°$, cf. inset in Fig. 1). In order to determine cross sections it is necessary to count the total number of incident ions. For this purpose a special beam monitor was developed.[7] The primary ion intensity is measured via x rays produced in a beam chopper added just in front of the target chamber. For the measurement of the angular dependence of x-ray emission a special target chamber was used. X-ray emission angles θ between 15° and 105° were feasible (target angle $\alpha = -30°$, cf. inset in Fig. 2). The beam intensity was monitored via x rays registered in a fix-positioned proportional counter. The 30-mm^2 Si(Li) detectors used had resolutions of 170 and 260 eV (full width at half-maximum) at 6.4 keV. In all cases pile-up rejection with at least 1-μsec pulse-pair resolution within the whole energy range was applied. To reduce the rate from lower-energy x rays, Al absorbers could be inserted between target and detector.

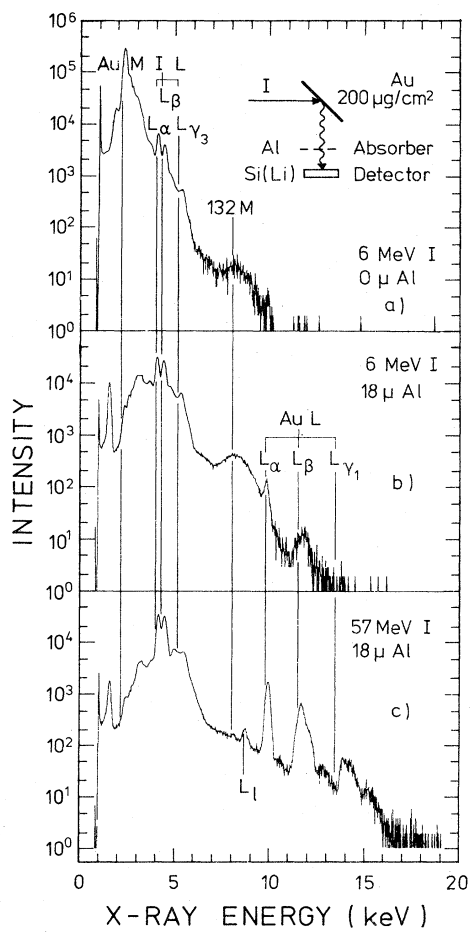

FIG. 1. X-ray spectra from I→Au collisions. (Detector resolution 170 eV at 6.4 keV.)

Figure 1 shows good resolved spectra from a 200-$\mu g/cm^2$ Au target. To determine the true spectral shape at low impact energies, spectrum (a) was taken without Al absorber. Absorption due to detector and target-chamber windows (0.3 mil Be, 5 mm air, 6 μm Hostaphan) and target self-absorption is only significant for lower-energy x rays. In the interesting energy range between 7 and 9 keV the total transmission varies by less than 2% per keV. Therefore, spectrum (a) definitively proves the existence of real peak structure. To get better statistics spectrum (b) was recorded with an 18-μm Al absorber. In both cases the count rates were low enough to ensure negligible pile-up contributions. A comparison of both these spectra indicates that at 6-MeV I impact the 8-keV band is composed of a broad peak (at 8.3 keV with a width of 1.5 keV) and a steeply descending continuum. With in-

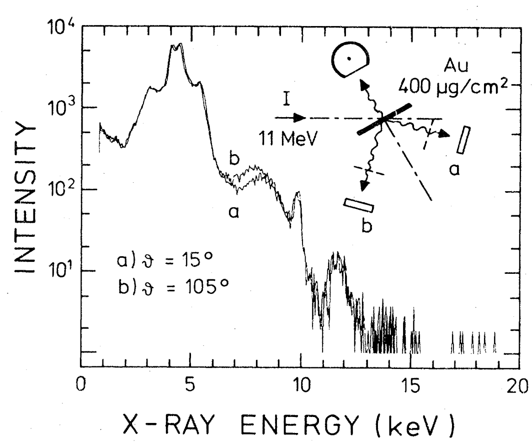

FIG. 2. Two x-ray spectra applying two different x-ray emission angles. (An 18-μm Al absorber is inserted between target and detector, detector resolution 260 eV at 6.4 keV.)

TABLE I. X-ray production cross sections (barns) for I→ Au collisions.

	I energy (MeV) 11	34	57
I L (3.6–6.5 keV)	4.0×10^3	2.5×10^4	9.5×10^4
MO (6.5–9.5 keV)	4.5×10^1	1.8×10^2	•••
Au L (9.5–14.5 keV)	6.5×10^0	2.3×10^1	8.0×10^2

creasing impact energy the peak broadens; at 57 MeV only a flat continuum is present, cf. spectrum (c) in Fig. 1.

In Table I total x-ray cross sections are given for the 8-keV band as well as for the characteristic radiations of the separated collision partners.[7] These cross sections correspond to x-ray emission within the energy ranges indicated in brackets. The typical uncertainty is below 50%; isotropic emission has been assumed.

In order to check the emission characteristic we have measured the angular dependence of the x-ray emission at 11 MeV. Figure 2 displays two spectra taken at a detector position θ of 15° and 105°, respectively. Target angle ($\alpha = -30°$) and emission angles were chosen in such a way that target self-absorption is equal for both detector positions. The spectra are normalized to equal beam intensity. Besides the small Doppler shift of the I L radiation a significant difference is only seen for the 8-keV band. In Fig. 3 the angular dependence of the x-ray emission for the 8-keV band is given. Each datum point comprises all x rays in the corresponding spectrum between 7.1 and 9.5 keV. All spectra were corrected point by point on absorption[8] and on the tails of the characteristic lines. Uncertainties due to these corrections and errors in beam monitoring add to the indicated uncertainty of 4%. A $\sin^2$ function is fitted through the data points, yielding a mean anisotropy of 15% for all x rays in the band. However, it should be noted that the anisotropy varies with x-ray energy, cf. Fig. 2, being largest between 7.5 and 8 keV.

Summarizing the experimental facts we point out: (i) At low impact energies the 8-keV band is peaked. (ii) The peak structure broadens and finally vanishes with increasing impact energy. (iii) At 11 MeV the cross section for x-ray production between 6.5 and 9.0 keV is about 50 b. (iv) At 11 MeV the x rays are preferentially emitted perpendicular to beam direction. Regarding these facts, significant contributions from nuclear bremsstrahlung and bremsstrahlung from δ rays can be excluded (cf. the spectral shape and the high cross sections).[6] Contributions from target contaminations and radiative electron capture are also negligible.[3,4] Only MO radiation remains to be responsible for the 8-keV band. However, it is difficult to explain quantitatively the data in the simple model based on a comparison of collision time and *spontaneous decay* time of the vacancy carried into the quasimolecule in a second collision.[3] To overcome this difficulty a *collisionally induced de-excitation* reducing the lifetime of the vacancy in the quasimolecule has been proposed in Ref. 3, cf. also Ref. 7. Recently, from a theoretical point of view, Müller, Kent-Smith, and Greiner have postulated the occurence of such induced transitions in heavy-ion collisions.[9] In their model the rotation of the internuclear axis during collision is responsible for induced radiative transitions. As consequences they find: (a) The ratio between induced and spontaneous emission increases rapidly with decreasing distance of closest approach (as long as small- or medium-angle scattering prevails). (b) This ratio increases with increasing collision velocity. (c) The induced x-ray emission is nonisotropic showing—in dipole approximation—an angular dependence given by $I(\theta) \propto \frac{1}{2} + \frac{1}{4}\sin^2\theta$.

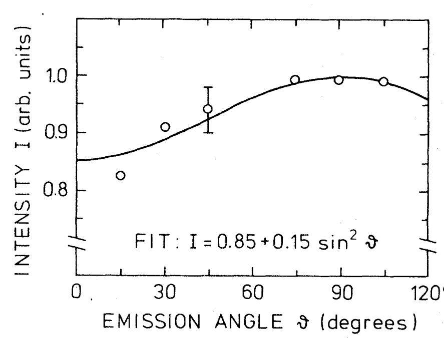

FIG. 3. Anisotropy of the noncharacteristic x rays between 7.1 and 9.5 keV for 11-MeV I impact on a 400-$\mu g/cm^2$ thick Au target.

This induced-emission mechanism has the appropriate features which in principle can explain the experimental results reported here: From point (a) the observed peak structure may be deduced. From point (b) the dependence of the spectral shape on impact energy may follow. The large cross sections can be caused by the reduced lifetime due to induced transitions. Finally, we would like to emphasize the principal agreement between observed anisotropy of the noncharacteristic x rays and the theoretical predictions. This can be regarded as a strong evidence for the existence of stimulated emission in heavy-ion collisions contributing appreciably to quasimolecular x-ray emission.

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